THE WEATHERING OF SANDSTONE, WITH PARTICULAR REFERENCE TO BUILDINGS IN THE WEST MIDLANDS, UK.

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ABSTRACT

The West Midlands contains a number of historic buildings constructed from local New Red Sandstones, which exhibit evidence of severe weathering. To identify and explain the mechanisms and weathering forms responsible for the deterioration of these buildings, and the influence of the environmental conditions in the West Midlands, selected experiments have been conducted. A microcatchment experiment highlighted that weathering mechanisms, associated with the deposition of atmospheric particles, hydrolysis of silicates and the formation of salts, operate on this sandstone. An exposure trial examined the influence of different environmental conditions upon these weathering mechanisms. No statistically significant differences were found between samples exposed in urban and rural locations. However, sheltering the samples from precipitation increased the accumulation of salts and atmospheric particles, but reduced dissolution and hydrolysis. Chemical and microscopic analysis of stone samples affected by different weathering forms, showed that differences in salt concentrations exist between weathering forms. To asses the importance of climatically induced cycles, a data logger controlled monitoring system recorded stone temperature and moisture conditions at Lichfield Cathedral. Thermal and moisture cycles, calculated for each of the four cardinal points, showed that aspect exerts a significant influence upon the occurrence and severity of these cycles. A quantitative survey of thirty sandstone buildings in the West Midlands, recorded the occurrence of different weathering forms, which were found to be influenced by environmental conditions. Weathering forms, associated with the deposition of atmospheric particles, affected up to four times more stone in urban areas than in rural areas, while weathering forms associated with autotrophic colonisation typically affected twice as much stone in rural areas than in urban areas. This pattern was largely attributed to the distribution of coal burning over the last 150 years. Aspect influenced the occurrence of weathering forms and it was shown that certain weathering forms, such as black flaking, occurred where thermal and moisture cycles were active, whilst others, such as granular disintegration, occurred under relatively stable temperature and moisture conditions. In general, weathering forms were shown to be polygenetic, with chemical and/or biological mechanisms operating initially, followed by physical mechanisms, causing the loss of stone. A model indicating the importance of different weathering mechanisms in the formation of specific weathering forms and their changing importance with time was formulated.

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INTRODUCTION

This thesis focuses on the weathering of sandstone buildings in the West Midlands region of England. The need for research into the weathering of sandstone is demonstrated by Young and Young (1992), who point out that the geomorphology of sandstone has been relatively neglected. This neglect is not justified, since sandstones occupy about 15% of the earth's land surface, which is twice as much as limestones, that have been extensively studied (Robinson and Williams, 1994a). As well as geomorphological research into the weathering of sandstone, research has been conducted into the decay of sandstones used for building. This has especially been the case in the last decade, with European research making the greatest contribution. Recent stone decay research in the UK is largely the result of criticisms, by the House of Commons Environment Committee in 1984, on the lack of research into the relationship between atmospheric pollution and damage to historic monuments. As well as concern over air pollution damage, impetus for research has been provided by the financial cost of repairing historic buildings and the realisation that effective restoration requires an understanding of the causes of deterioration. This has been highlighted in the UK by the inadequacy of cleaning techniques on sandstone buildings (Bluck and Porter, 1991a). Further north and west in England, the importance of sandstone as a building material increases. Despite this, the majority of research into stone decay has concentrated on limestones. It was this relative neglect of sandstone weathering, by geomorphologists and stone decay researchers, that initiated this research programme. The occurrence of sandstone and it's use as a building material is widespread in the West Midlands. The initial objective of the research was to identify and explain the mechanisms and weathering forms responsible for the deterioration of sandstone buildings in relation to the environmental conditions of the West Midlands, England. Due to the development of the West Midlands, historic sandstone buildings, in the centre of the region, have been subjected to considerable atmospheric pollution since the nineteenth century. The periphery of the region is typically rural, allowing the effects of atmospheric pollution upon sandstone weathering to be studied.

A diagrammatic representation of the layout of this thesis is presented in Figure 1. Chapter 1 introduces the weathering mechanisms most applicable to sandstone, while

Chapter 2 examines how weathering affects sandstone buildings. Following these introductory chapters, the specific aims of the research, the study area and the experimental design, are presented in Chapter 3. Details of experimental methods, results and discussion appear in Chapters 4 and 5. An integrated and more extensive discussion of the findings and their implications is presented in Chapter 6, while a summary of the conclusions and further work appear in Chapter 7.

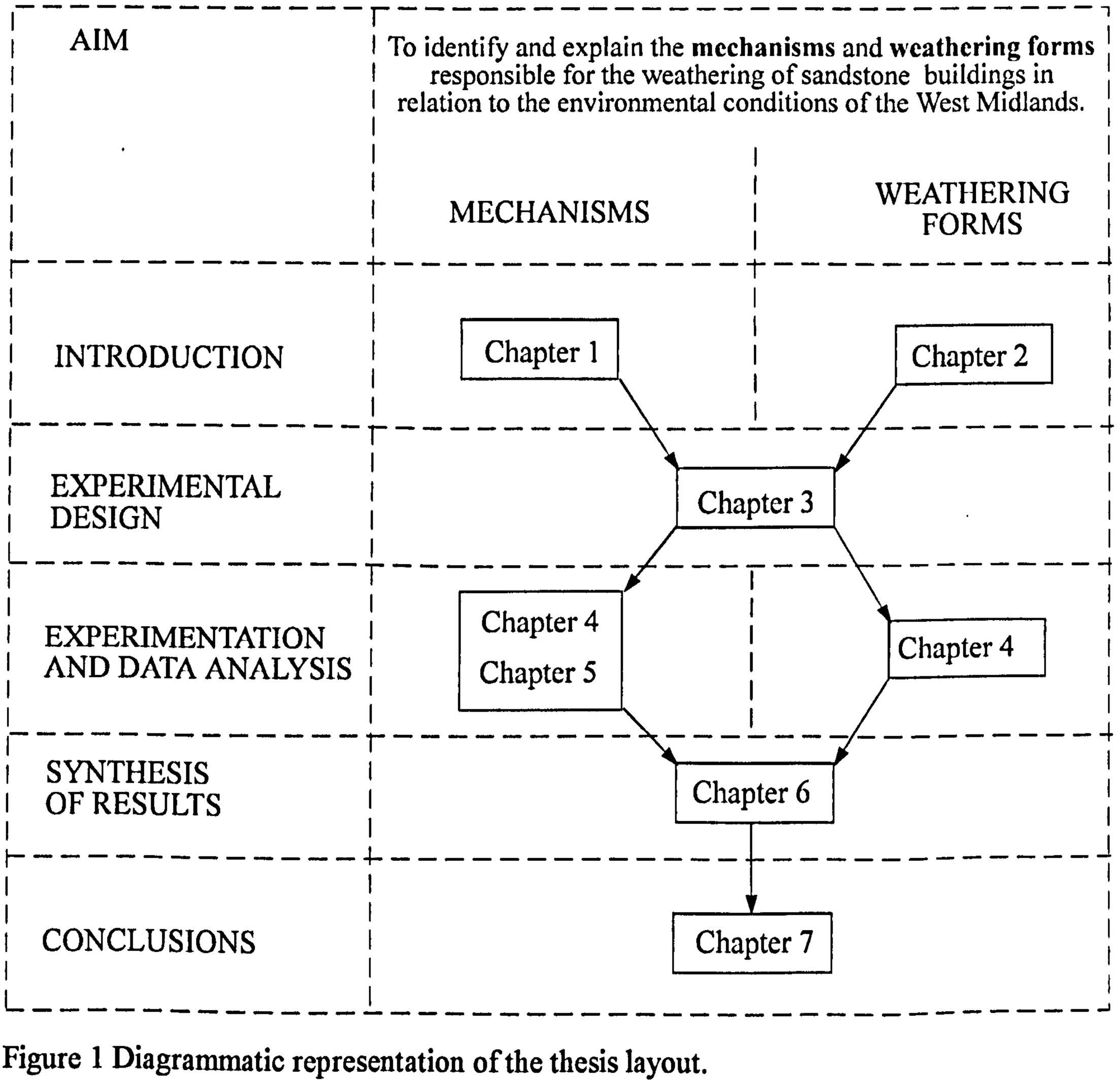

Figure 1 Diagrammatic representation of the thesis layout.

CHAPTER 1

SANDSTONE WEATHERING MECHANISMS

1.1 INTRODUCTION

In this study, the term weathering refers to any breakdown or alteration of sandstone, to products that are nearer to equilibrium with the newly imposed physio-chemical conditions (Ollier, 1984). A great deal of literature exists on rock weathering processes and for a general account Ollier (1984) provides an overview from a geomorphological view point, while Amoroso and Fassina (1983) provides an overview to the research conducted into building stone decay. These two areas of research provide a vast body of literature. It is the aim of this chapter to introduce the weathering mechanisms appropriate to sandstone and more specifically those believed to be appropriate to sandstone buildings in the West Midlands. This will enable Chapter 2 to concentrate on the manifestation of these weathering mechanisms on the buildings themselves and consider the spatial variations in sandstone weathering.

Weathering is principally controlled by the composition and structure of the rock, the nature of the climate and time of exposure. However, there are many uncertainties about how processes achieve weathering and why they vary so greatly for different stones or climates (Robinson and Williams, 1994b). The processes and factors controlling weathering mechanisms are more complex than previously thought and the studying of weathering mechanisms is complicated by the long time spans over which they operate. Consequently, many researchers have conducted accelerated laboratory tests, but the speeding up of weathering casts serious doubt on the validity of the findings (Robinson and Williams, 1994b).

Geomorphologists have traditionally divided weathering mechanisms into three basic categories; physical, chemical and biological. In reality the complexity of weathering mechanisms means that a weathering agent can exert a physical, chemical and even a biological influence at one time. However, this division into three categories has been shown to be useful by geomorphologists and will be used in this chapter, but it must be

considered that these categories are not exclusive from each other.

1.2 PHYSICAL WEATHERING MECHANISMS

1.2.1 INSOLATION WEATHERING

Warke and Smith (1994) point out that disagreement exists over the importance of changes in stone temperature in causing the weathering of stone, insolation weathering. Young and Young (1992) consider that the breakdown of sandstone by thermal stresses is substantial and the effects of fatigue are supported by field observations. However, early experiments (e.g. Blackwelder, 1933 and Griggs, 1936) failed to measure insolation weathering despite early field observations (e.g. Brown, 1924) which supported the theory. Since these early observations, the theory of insolation weathering has been further scrutinised by geomorphologists who generally recognise a failure to correlate simulation experiments with field observations. The cause of this poor correlation is open to debate, however experiments simulating insolation weathering must be evaluated with care. In general, they require simplifications of environmental conditions, fail to reproduce any fatigue factor and expose samples in an unconfined condition.

The importance of stone being confined, has been demonstrated by Gray (1965). Complete constraint in all directions parallel to the surface was found to be necessary for spalling to occur. Gray (1965) demonstrates that, even if external constraints are not present, a state similar to complete constraint is achieved if the rock is not heated uniformly and the thickness of the heated layer is not too great. Therefore, the essential condition is that a thermal gradient is set up, suggesting that the severity of insolation weathering is not associated with the temperature of the stone, but with the internal temperature gradient (Gray, 1965).

Temperature gradients depend on the thermal conductivity of the stone. If thermal conductivity is low, the surface of the stone will reach a higher temperature, as less heat is conducted to other parts of the stone. This causes a steeper thermal gradient and greater stress. Furthermore, lower rates of heating and cooling will be experienced in the subsurface. The importance of this has been demonstrated by Warke and Smith (1994) for

Dunhouse Sandstone (Figure 1.2.1). The slower rate of heating and cooling in subsurface layers causes surface temperatures to drop when cooling conditions prevail, while subsurface temperatures continue to rise. This causes the subsurface to be warmer than the surface, creating compressive stress as the surface contracts and the subsurface expands. During heating, tensile stresses develop between the surface and the subsurface, as the surface is expanding quicker than the subsurface. This reversal in the direction of the stress, experienced by the stone, may in time cause fatigue, especially in stones with low thermal conductivity and low albedos (Warke and Smith, 1994). Fatigue occurs where variations in applied stress cause the stone to fail at a stress level, the fatigue limit, far below the strength of the stone, as determined by conventional testing.

Fatigue effects may occur as a response to diurnal expansion and contraction cycling, as well as additional cycles operating several times a day (Warke and Smith, 1994). However, in addition to fatigue effects, differential thermal expansion of the sandstone may occur. Minerals contained in the stone expand at different rates, but also rates of expansion differ along each crystallographic axis (Table 1.2.1). Since sandstones contain several different minerals, generally occurring in random orientations, expansion rates between mineral grains will not be the same, causing stress. A limited degree of mineral orientation may occur along bedding planes and therefore expansion parallel to the bedding plane may differ from that perpendicular to the bedding plane (Table 1.2.1). In addition to differential thermal expansion, caused by properties of the stone, Galan *et al.* (1992) comments that superficial degradation alters the thermal and strength properties of localised patches of stone, causing differential expansion between these areas. As a result of this, Galan *et al.* (1992) reports that marble columns are significantly degraded by insolation weathering.

1.2.2 MOISTURE CYCLES

Some scepticism exists over the effectiveness of insolation weathering and Yatsu (1988) believes that water is needed for insolation weathering to occur. This may be due to the simple fact that water reduces the tensile strength of the stone. However, moisture content can increase the thermal expansion of stone. As the capillary water in the pores of the stone is under surface tension it causes compression of the grains of the stone. If temperature

increases, surface tension decreases, as does the corresponding compression (Domone, 1994). Therefore, extra expansion of the stone occurs.

Expansion and contraction of stone due to wetting-drying may occur due to various physical mechanisms, summarised in Table 1.2.2. Weathering of sandstones containing swelling clays, due to repeated wetting and drying has been reported by Young and Young (1992). In a similar way expansion of organic matter, such as algae and fungi, due to wetting and drying may cause weathering (Ortega-Calvo *et al.*, 1992).

1.2.3 FREEZE-THAW MECHANISMS

As liquid water changes phase to ice, a 9% increase in volume is experienced. This expansion has traditionally been considered as an effective weathering mechanism in cold regions (Ansted, 1871). However, freeze-thaw is also believed to be active in temperate climates. For example, Fobe *et al.* (1993) believe that freeze-thaw may be a cause for weathering of sandstone buildings in NE Belgium. Smith *et al.* (1994) considers that catastrophic weathering of sandstone buildings may be caused by freeze-thaw.

The effectiveness of freeze-thaw is dependent on a range of rock properties, but also, moisture availability, intensity of freezing, and amplitude and number of freeze-thaw cycles. A thorough review of freeze-thaw mechanisms and factors influencing their effectiveness as weathering agents is provided by McGreevy (1981).

McGreevy (1981) presents five hypotheses for freeze-thaw weathering:

a. *Volumetric expansion of water.* The pressure generated by the 9% increase in volume associated with freezing has been shown to theoretically produce great pressures (Bridgeman, 1912). However, when considering the pressure exerted on to the stone, it must be remembered that the water will rarely be confined and may not fill the pores totally. In general, the stone needs to be highly saturated, freezing must be reasonably rapid and it may be necessary for air temperatures to drop to -5^{o}C.

b. *Crystallisation pressure of ice.* This theory is based on the fact that crystals will grow in directions where growth is opposed by external forces. This same theory applies to the crystallisation of salts. The pressures exerted by the growth of ice crystals are considerably less than those created by the volume change associated with freezing. A limiting factor is the supply of water to the growth face which will be favoured by an open porous system and slow freezing.

c. *The capillary theory of frost damage.* The controlling factors for this theory are the grain size, amount of free water, size and percentage of voids and rate of freezing. The principle is based on the fact that not all water freezes at the same temperature, making flow to ice centres possible. As the crystals grow they displace overlying material. Unlike volumetric expansion, it is essential that freezing occurs slowly in an open system, so that water can move to growing centres. It can be shown that the pressure generated by ice forming in a stone is related to the difference in size between pores and interconnecting capillaries. Honeyborne and Harris (1958) showed that limestones susceptible to frost weathering had a large percentage of pores below 0.005 μm. These pores were absent for resistant limestones.

d. *The ordered water hypothesis.* Water becomes ordered at low temperatures, in other words individual molecules assume a particular orientation. The layer of water covering pore walls becomes polar, with positive charges on the hydrogen side and negative charges on the oxygen side. In small pores, <5 μm in diameter, layers of ordered water exist on opposite walls of the pore, repelling each other due to the like charges on their free sides. As temperatures drop the alignment of the molecules improves, causing repulsive forces to increase. This mechanism is more effective if clays are present due to their higher surface area per unit volume.

e. *Hydraulic pressure hypothesis.* This assumes that the surface of the stone is close to saturation before the onset of freezing. Freezing starts at the surface, forming a seal. Water behind this seal freezes and as it does the pressure generated pushes the remaining water

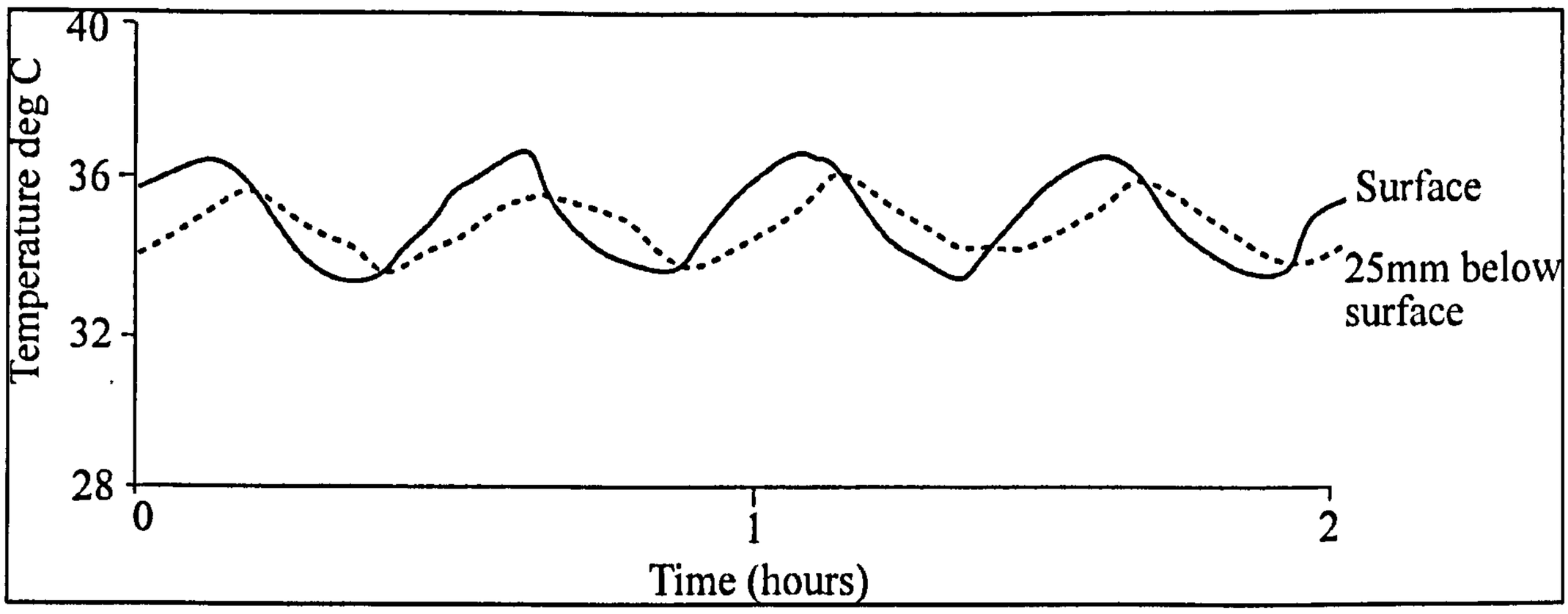

Figure 1.2.1 Rock surface and subsurface (25 mm depth) temperatures recorded in a simulation experiment (After, Warke and Smith, 1994).

Mineral/stone	Orientation	Mean coefficient of linear thermal expansion ($\times 10^{-6}\ ^{o}C^{-1}$)	Reference
Quartz	Perpendicular to *c*-axis	13.5	Johnson and Parsons (1944)
Quartz	Parallel to *c*-axis	7.4	"
Microcline	Parallel to *b*-axis	1.1	"
Microcline	Parallel to *a*-axis	17.1	"
Orthoclase	Parallel to *a*-axis	15.0 *	Kozu and Saiki (1925)
Orthoclase	Parallel to *b*-axis	0.0 *	"
Sandstone	Parallel to bedding plane	9.2	Hockman and Kessler (1950)
Sandstone	Perpendicular to bedding plane	9.5	"

Table 1.2.1 Mean coefficients of linear thermal expansion of selected minerals and sandstone between -20°C and 60°C (* temperature range 20°C to 100°C). Crystallographic axes are defined as follows: the *a*-axis is the back-to-front axis, the *b*-axis is the left-to-right axis and the *c*-axis is the vertical axis.

Mechanism	Explanation
Capillary tension	Free water in the pores of the stone is under surface tension. As water evaporates the surface tension increases. This causes compressive stresses in the surrounding grains and, therefore, shrinkage of the stone. When the pore empties, to a degree where the surface tension breaks down, the stress drops and the shrinkage recovers.
Surface tension	As with water, the surface of solids is under tension and the compressive stresses become significant for very small particles. Adsorption of water lowers the surface tension of the solid, leading to a reversible expansion.
Disjoining pressure	In a pore, adsorbed water forms a layer on the surface of solids, which are under pressure from surface attractive forces. In very narrow regions of the pore, the water between the grains will be in a state of hindered adsorption, creating a swelling pressure. On drying, the thickness of the adsorbed water layer reduces, causing a reduction in the area of hindered adsorption. This reduces the swelling pressure, resulting in shrinkage.
Movement of interlayer water	The three mechanisms above are concerned with free water (not under the influence of mineral surface attractive forces) or adsorbed water (under the influence of mineral surface attractive forces). The third type of evaporable water is the interlayer water (under the attractive forces of two very close mineral surfaces). Its intimate contact with the solid surfaces suggest that a large hygrometric gradient is necessary to remove it. However, the amount of shrinkage is likely to be high compared to the movement of an equal amount of free or adsorbed water.
Movement of chemically combined water	Water is chemically combined with minerals due to hydration reactions. Certain salts may occupy several hydration phases, which are influenced by moisture availability. As with interlayer water large hygrometric gradients are typically required to remove this water, but shrinkage is likely to be high.

Table 1.2.2. Mechanisms causing expansion and contraction of sandstone due to moisture availability. Adapted from theories presented by Domone (1994).

towards the less saturated interior. If this water is being forced through fine pores a hydraulic pressure will be generated, which may cause damage.

None of these hypotheses have been accepted or refuted. In general, opinions are inconclusive about the mechanisms and effectiveness of freeze-thaw as a weathering agent. It is also unlikely that one mechanism will function alone and the importance of each mechanism will be influenced by the properties of the rock and the environment.

1.2.4 SALT WEATHERING

Salts are generally reported as an important agent, causing the weathering of sandstone. Indeed, Fobe *et al.* (1993) and Smith *et al.* (1994) consider that the majority of breakdown of sandstone is associated with salts, especially gypsum. The fact that salts are powerful weathering agents has been utilised to test the durability of building sandstones (Leary, 1986). The variation in the resistance of sandstones to salt weathering is vast and measurements of porosity and saturation coefficients give no indication to durability (Leary, 1986). Granular disintegration of sandstone can be achieved by the crystallisation of salts close to the surface of the stone, which then experience heating-cooling and wetting-drying cycles (Smith *et al.*, 1982). Sandstone scaling occurs due to the expansion and contraction of salts, totally filling the pores in the subsurface of the stone (Smith and McGreevy, 1988).

For stones incorporated into a building, salts may be derived from the atmosphere, and the dissolution of soluble components of the stone and adjacent material (Sabbioni and Zappia, 1992). The formation of salts, especially gypsum, due to atmospheric inputs has been well documented. In addition to atmospheric inputs, road deicing salt (Smith *et al.*, 1991a; Winkler and Singer, 1972) and rising ground water (Smith *et al.*, 1991a; Agrawal *et al.*, 1986) cause weathering near to ground level. Many different salts may be formed in sandstone. Lofvendahl, *et al.* (1992) reported thirty-four different salts in sandstone from Sweden. Thirteen salts were sulphates, twelve carbonates, five chlorides and four nitrates.

Although salts have the potential to be powerful weathering agents, the exact mechanisms involved in salt weathering are harder to define. There are three different physical mechanisms that are considered capable of generating pressures within the pores or fissures of a stone.

a. *Crystallisation pressure.* When a salt solution evaporates it becomes more saturated, eventually the solute concentration exceeds the saturation point and salt crystals are formed. The crystals grow in the pores of the stone, but as they grow they generate stress on the sides of the pores (Cooke and Gibbs, 1995). The saturation point may also be reached due to a drop in temperature. The relative importance of these two crystallisation processes depends on the environmental conditions, but Goudie (1985) notes the latter can affect a large volume of solution and may, therefore, affect a greater volume of stone. Theoretically, the larger the change in volume upon crystallisation the more damaging a salt will be. Data on crystallisation pressures for salts, commonly occurring in stone, can be found in Table 1.2.3.

b. *Hydration pressures.* Some salts have more than one hydration phase, with the volume of the salt increasing as the salt takes up more water. As with crystallisation, the greater the change in volume, the greater the potential for stress generation and damage to the stone. The pressure generated depends on the salts present. For example, sodium sulphate increases in volume by 315% upon hydration, gypsum increases by 42% and halite does not undergo hydration (Goudie, 1985). Measurements of expansion and contraction of Portland Limestone impregnated with $MgSO_4$, suggest that crystallisation pressures are greater than hydration, but find that repeated hydration cycles can cause cracking (Cooke and Gibbs, 1995).

c. *Differential thermal expansion.* Inequalities between the thermal properties of the salts and those of the stone result in differential thermal expansion as discussed in Section 1.2.1.

Salt weathering may be enhanced for clay rich sandstones, possibly due to the increase in microporosity (McGreevy and Smith, 1984) or due to the presence of swelling clays (Bluck,

1992). Some salts greatly enhance the effectiveness of freeze-thaw (Williams and Robinson, 1981). As well as physical mechanisms, salts may cause chemical weathering, as highly saline solutions may have a pH above 9 and this increases silica solubility (Goudie, 1985). Young and Young (1992) consider that, for some forms of weathering, the influence of salt is related, more to its influence on rates of solution, than physical mechanisms. Also salts are hygroscopic, therefore absorb moisture from the air when the relative humidity is greater than 70% (Masonry Conservation Research Group, 1992). Hudec and Rigbey (1976) found sodium chloride increased water absorption and the degree of saturation. Therefore, salts may increase the moisture supply to the stone, which may increase chemical and biological weathering.

1.3 CHEMICAL WEATHERING MECHANISMS

A great deal of literature exists on the chemical weathering of stone. General reviews are provided by Ollier (1984) and Keller (1968). Chemical weathering mechanisms are dependent on the mineralogy of the stone and the exposure environment. In this section, the mechanisms most appropriate to sandstone in the West Midlands will be considered. Exposure trials with sandstones suggest that chemical weathering of sandstone occurs due to dissolution (Steiger *et al.*, 1993), sulphation (Sweevers and Van Grieken, 1992) and hydrolysis of silicate minerals (Halsey *et al.*, 1995a).

Due to a lack of equilibrium between a stone and its exposure environment, minerals in the stone are thermodynamically unstable (Lofvendahl, 1992). As a result, all minerals are to some extent soluble in water. Stumm and Morgan (1981) created the following list, which indicates increasing solubility at the earth's surface: haematite, kaolinite, muscovite, quartz, albite, orthoclase, calcite, gypsum, halite. Calcite typically occurs as a cementing material, therefore its loss may result in weakening of the stone. Direct dissolution of calcite has been suggested by Steiger *et al.* (1993). However, sulphation with atmospheric SO_x to form gypsum, followed by dissolution, is generally reported as the dominant reaction (Equation 1.3.1).

For many sandstones, quartz and other silicate minerals form the bulk of the stone. There is widespread belief that quartz rich sandstones are chemically inert, however, fine examples of karstic terrain are found on quartz arenites, calling for the chemical weathering of sandstones to be re-examined (Young and Young, 1992). Robinson and Williams (1994a) also consider that the dissolution and mobility of silica is important and the influence of physical weathering may have been over emphasised. Puhringer *et al.* (1992) reported a surface crust of amorphous silica formed by the chemical weathering of sandstone. This crust reduced water absorption and had a zone of decohesion below the surface.

Most dissolution of silica is thought to come from silicates as opposed to quartz. Silicates may undergo hydrolysis to leave a clay or amorphous silica. Hydrolysis of orthoclase to kaolinite has been suggested by Halsey *et al.* (1995a) and this releases silica ions (Equation 1.3.2). The clay or amorphous silica may be subjected to further weathering and amorphous silica is much more soluble than quartz. However, the solubility of quartz may be similar to amorphous silica if surface disturbances are present or the environment is saline (Young and Young, 1992). Morris and Fletcher (1987) suggest that ferrous iron reacts with quartz surfaces, causing dissolution of quartz to be about 1 000 times greater than expected. Furthermore, the volume of water passing through the rock is very important (Young and Young, 1992).

1.4 BIOLOGICAL WEATHERING MECHANISMS

Biological weathering or biodeterioration causes stone degradation by the organism exerting physical and chemical influences (Huek-van der Plas, 1968). Biological weathering has traditionally been considered by geomorphologists. However, in recent years biologists working on masonry deterioration have contributed greatly to the understanding of the biodeterioration of stone. A comprehensive review is provided by Bock and Sand (1993), which highlights that the biodeterioration of sandstone has received appreciable attention, being considered in almost half of the references cited.

Physical mechanisms result from the penetration and exploitation of pores or fissures in the stone by the growing organism. As the organisms typically contain water they may increase

freeze-thaw activity. However, the expansion and contraction of the organism due to moisture cycles is probably of greater importance (Ortega-Calvo *et al.*, 1992). Chemical mechanisms are also important as the majority of organisms generate various chemicals that attack stone in order to extract nutrients for growth (Lofvendahl, 1992). These are generally organic acids, however some bacteria form sulphuric acid, which may increase the formation of sulphates. Indeed, Vendrell-Saz and Garcia-Valles (1992) consider that organic matter and micro-organisms may catalyse gypsum formation. Palmer *et al.* (1991) consider the chelation activity of organic acids to be of greater importance than acid attack. Chelation involves the holding of an ion, usually a metal, in a compound of organic origin. It is used by plants to extract ions in environments where they would normally precipitate.

The organisms reported on sandstones can be classified as bacteria, fungi, algae and lichens. The literature review conducted by Bock and Sand (1993) suggests that fungi and bacteria are most numerous. Huek-van der Plas (1968) consider that nitrogen and sulphur oxidising bacteria are the most damaging. Fungi are heterotrophic, their energy is derived from the digestion of organic matter. Ortega-Calvo *et al.* (1992) consider that bacteria and algae are important for supporting fungal growth, which they consider to be very destructive. Algae require light for growth and are generally considered the least damaging group of organisms. However, they do exert physical mechanisms and support fungal growth. Lichens, which are organisms with a symbiotic relationship between fungi and algae, have been extensively studied. They occur widely on natural rock surfaces and building stone. They have a tendency to form crusts and this causes them to have a great visual impact. It is partly this characteristic that has resulted in their extensive study. A detailed review of stone weathering by lichens is provided by Jones and Wilson (1985). It is generally thought that the fungal component of the organism attacks the stone by acid attack and chelation. Jones and Wilson (1985) believe that once chemical deterioration has reached a critical level, the physical stresses exerted by the wetting-drying of the lichen crust become important and detachment of the surface layer results.

1.5 SUMMARY

Weathering of stone may occur by physical, chemical and biological agents. Insolation weathering may cause significant weathering if a large thermal gradient is established or superficial degradation has taken place. Moisture may exacerbate insolation weathering. However, expansion and contraction due to moisture cycles may also cause weathering. Freeze-thaw activity may cause weathering, although opinion on the actual mechanisms causing deterioration is divided. Salts are a major weathering agent, with a wide range of salts identified on sandstone. However, gypsum predominates in continental urban environments. Evidence suggesting the actual mechanism of salt weathering is inconclusive and more recently the chemical influence of salt has received considerable attention. Due to the chemical influences of salt, the importance of chemical weathering of sandstones may have been under estimated and silica solubility may be more important than previously thought. Biological weathering results mostly from bacteria, fungi, lichens and algae, which cause deterioration by chemical and physical mechanisms.

This chapter highlights the complicated and associated nature of sandstone weathering mechanisms. The importance of different weathering agents and the corresponding mechanisms have been considered. This will allow Chapter 2 to consider the manifestation of these weathering mechanisms on sandstone building and examine the spatial variability of sandstone weathering.

Salt	Chemical formula	Crystallisation pressure			
		$C/C_s = 2$		$C/C_s = 10$	
		0°C	50°C	0°C	50°C
Anhydrite	$CaSO_4$	335	398	1120	1325
Bischofite	$MgCl_2.6H_2O$	119	142	397	470
Dodekahydrate	$MgSO_4.12H_2O$	67	80	222	264
Epsomite	$MgSO_4.7H_2O$	105	125	350	415
Gypsum	$CaSO_4.2H_2O$	282	334	938	1110
Halite	NaCl	554	654	1845	2190
Heptahydrite	$Na_2CO_3.7H_2O$	100	119	334	365
Hexahydrite	$MgSO_4.6H_2O$	118	141	395	469
Kieserite	$MgSO_4.H_2O$	272	324	910	1079
Mirabilite	$Na_2SO_4.10H_2O$	72	83	234	277
Natron	$Na_2CO_3.10H_2O$	78	92	259	308
Tachhydrite	$2MgCl_2.CaCl_2.12H_2O$	50	59	166	198
Thernadite	Na_2SO_4	292	345	970	1150
Thermonatrite	$Na_2CO_3.H_2O$	280	333	935	1109

Table 1.2.3 Crystallisation pressures for some salts. C/C_s is degree of super saturation where C is the solute concentration and C_s is the saturation concentration. (After, Winkler and Singer, 1972).

$$CaCO_3 + SO_3 + 2H_2O \rightarrow CaSO_4.2H_2O + CO_2$$

Equation 1.3.1

$$4KAlSi_3O_8 + H^+ \rightarrow Al_4Si_4O_{10}(OH)_8 + 4K^+ + 8Si^+ + 14O^{2-}$$

Equation 1.3.2

CHAPTER 2

THE MANIFESTATION OF SANDSTONE WEATHERING ON BUILDINGS

2.1 INTRODUCTION

Consideration of the various sandstone weathering mechanisms highlights the variable manner in which stone may weather. Furthermore, individual weathering mechanisms are not isolated from one another and may have interactive effects. Therefore, the appearance of a weathered sandstone surface may result from many mechanisms, the importance of which may vary over the period of weathering. Also, the importance of each mechanism will be influenced by the properties of the stone and the nature of the environment. Therefore, spatial variations in the manifestation of weathering may be expected and indeed, visually distinct weathering forms can be identified. In this chapter a review of the weathering forms reported on sandstone buildings is presented, followed by an examination of their spatial variation.

2.2 THE NATURE OF SANDSTONE WEATHERING

A study of crust formation on calcareous sandstones in Italy reports black crusts covering stonework (Sabbioni and Zappia, 1992a). The crusts are composed of a thin (<10 mm) black gypsum layer overlying a thicker (>10 mm) layer of white powder. This morphology is attributed to the calcium carbonate cement of the stone being converted to gypsum, by sulphation with atmospheric SO_X, and then dissolved. The evaporation of the resulting solution occurs at the surface of the stone, causing gypsum to concentrate in the outer layer, leaving an un-cemented layer behind (Sabbioni and Zappia, 1992a). As the gypsum precipitates at the surface of the stone, pollutants, typically carbonaceous particles, are embedded into it, giving the black appearance. Lofvendahl *et al.* (1992) considers that blackening may be due to particles from combustion, tyres, asphalt and soil. The lack of cohesion of the underlying powder causes the black layer to detach, allowing the powdered stone to be eroded. This process causes a loss of material, about 10 mm thick, and initiates a new cycle of weathering (Sabbioni and Zappia, 1992a).

Gypsum crusts also occur on sandstone buildings in Florence (Malesani and Vannucci, 1974). In this instance gypsum formation is ascribed to the activity of bacteria. Smith *et al.* (1994), examining Quartz Arenites in Belfast, suggest that black crusts result from inorganic airborne particles (e.g. fly ash), organic airborne particles (e.g. pollen), inorganic precipitates (e.g. gypsum) and organic growth. The crust eventually forms a lattice of gypsum laths, enclosing these particulates. Bluck and Porter (1991a) presented a model of crust formation where algae and pollutants adhere to the surface, while the stone is wet, but are fixed as the stone dries. The crust builds up until moisture ingress-egress is no longer possible, causing detachment of the crust (Figure 2.2.1).

Peeling crusts have also been noted on ferruginous sandstone in north-eastern Belgium (Fobe *et al.*, 1993). Analysis shows the crusts consist of gypsum, even though the stone contains little calcium. Bos and Gullentops (1990) state deterioration of the same sandstone, from Belgium, is enhanced by calcium from other materials within the building structure, such as lime mortars and limestone. However, low concentrations of gypsum were also detected on a rural sandstone outcrop, with no obvious source of calcium (Fobe *et al.*, 1993). It may be that gypsum is deposited directly on to the stone from the atmosphere (Smith *et al.*, 1994).

An examination of sandstone buildings in California by Twilley and Podany (1986), noted crusts which were not blackened, but similar in colour to the underlying stone. This was due to the incorporation of material from within the stone. This weathering feature, termed case-hardening, occurs due to the deposition of solutes by pore water, that has been drawn to the surface of the stone and evaporated. The crusts may be coloured by iron, manganese or titanium. However, generally redeposited silica is the most important component (Robinson and Williams, 1994a). Bluck (1992) describes a case hardened stone, where iron oxide cement has been deposited at the surface and detachment occurs due to the loss of cement in the underlying zone. Lofvendahl *et al.* (1992) report a sandstone suffering from crust formation to have increased levels of sulphur and iron, which may be derived from the weathering of pyrite. Nord *et al.* (1990) attribute blackening partly due to iron derived from the stone. In addition to this, detachment of layers of sandstone with no obvious

surface alteration, such as case hardening or black crusts, have been observed on buildings in Belfast (Smith *et al.*, 1994).

In a detailed examination of crust detachment processes, Wendler *et al.* (1990), show that clay rich sandstones, exposed to sun, wind and driving rain, are most prone to crustal detachment, due to rapid swelling and shrinking. Wendler *et al.* (1990) note that stones with crusts consist of an undamaged inner zone, a weak middle zone and the outer crust. The middle zone is weakened even in stones where crust formation is not externally visible. By using computer simulated moisture distributions, Wendler *et al.* (1990) identified different moisture properties in the three zones. The inner zone, at depths greater than 30 mm, is unaffected by wetting and drying cycles. In contrast, the surface zone is characterised by rapid wetting and drying cycles to a depth of about 8 mm. The middle zone experiences rapid wetting, but delayed drying, making this the last area to dry and as a result soluble salts concentrate in this zone. Wendler *et al.* (1990) suggest that the salt concentration destabilises the orientation of clay minerals. These structural alterations, as well as the mechanical stresses generated by salt weathering and swelling-shrinking, reduce the middle zone to small brittle pieces, allowing detachment of the outer scale. Smith and McGreevy (1988) used a simulation experiment to show that detachment of crusts can be caused by salt stresses underlying the crust, which cause micro-fracturing of quartz grains (Figure 2.2.2).

Salt crystallisation at depth is instrumental in causing crustal detachment, whereas crystallisation at the surface causes granular disintegration (Smith *et al.*, 1992). Granular disintegration, also known as 'sanding', occurs when grains of the stone detach from the surface, due to the loss, or the physical break down of the cementing material. Agrawal *et al.* (1986), Lofvendahl *et al.* (1992), Smith *et al.* (1994) and Fobe *et al.* (1993) have all observed granular disintegration on non calcareous sandstone. When crusts detach from a surface, rapid breakdown can result. This may be in the form of granular disintegration (Sabbioni and Zappia, 1992) or multiple flaking (Smith *et al.*, 1994). Multiple flaking often, but not exclusively, occurs once a scale has detached. However, the mechanism of

formation is not clear, but their occurrence parallel to the exposed face suggests that they may be related to cycles of heating-cooling or wetting-drying (Smith *et al.*, 1994).

Sandstone weathering may not be uniform over the surface of the stone. This may be due to the geological structure of the stone. This is often caused by heterogeneous cementation of bedding planes, giving rise to a layered structure (Fobe *et al.*, 1993). In sandstones where sediments underwent strong bioturbation before diagenesis, a skeleton of tubular structures may be seen upon weathering. This is due to the walls of the burrows having superior cementation than the surrounding sediment, therefore they are more resistant to deterioration (Fobe *et al.*, 1993). Smith *et al.* (1994) notes granular disintegration to exploit individual beds of the stone, due to clay swellage and salt action. The decay of feldspar is an important factor, leading to differential weathering of Indian sandstone sculptures (Agrawal *et al.*, 1986). The sculptures were pitted due to the high porosity (45%), facilitating the weathering of less durable patches of feldspar rich stone, to form clays and bicarbonates, which were subsequently eroded (Agrawal *et al.*, 1986).

Heterogeneous sandstone weathering may not always be related to the geological structure of the stone. Many authors report pits or depressions in the stone, generally referred to as alveolar or honeycombing, that are not distinctly related to the structure of the stone. Sabbioni and Zappia (1992) report pits, generally 10 to 30 mm in diameter, closely packed on the surface of the stone to give a honeycomb appearance. In some highly exposed buildings mechanical abrasion with particles transported by the wind has been considered as a cause. However, as a whole aeolian abrasion is a negligible phenomena (Malesani and Vannucci, 1974) and Young and Young (1992) are in no doubt that alveolar are not the result of wind erosion. Examination of alveolar in coastal environments reveals that their occurrence increases with exposure, especially to salt laden winds (Mottershead, 1994) and solar radiation (Takahashi, *et al.*, 1994).

Once alveolar have formed they are protected from rain wash, allowing salts to concentrate and decay to accelerate (Smith and McAlister, 1986). Robinson and Williams (1994a) acknowledge that alveolar form due to salts, but consider that the evidence is inconclusive

on whether this is due to physical disruption, or an increase in silica dissolution (Young, 1987). Indeed both may occur, but in some cases little or no salt is found (Robinson and Williams, 1994a).

2.3 SPATIAL DISTRIBUTIONS OF SANDSTONE WEATHERING

Analysis of the spatial distributions of sandstone weathering can be carried out at several scales, ranging from macro, to meso, to micro scale. In this research, the macro scale will refer to variations due to distinct regional differences. For example, a difference caused by the urbanisation or industrialisation of an area. The meso scale refers to variations on a building. For example, the effects of aspect or differences in shelter. The micro scale will be concerned with variations between individual building stones or within individual building stones.

2.3.1 MACRO SCALE

Examination of regional variations in the weathering of sandstone buildings in Italy shows that sandstone buildings in rural areas have slight weathering, with only patches of lichen and algae present. However, buildings in the city of Bologna are blackened with gypsum crusts (Sabbioni and Zappia, 1992a). Fobe *et al.* (1993) notes sandstone buildings in rural areas tend to have lower gypsum concentration than those in urban areas.

2.3.2 MESO SCALE

The study of limestones and marbles has concluded that the decay of these stones varies in relation to the washing effect of rainfall. The commonly observed pattern is a black damage crust of gypsum, in sheltered areas, and a white surface, in areas washed by rain. However, Sabbioni and Zappia (1992) noted that the blackening of sandstone buildings occurs on the whole surface independent of its geometry or exposure to rain water. Due to the physical structure of sandstones, polishing of the surface is not possible and as a result sandstones have a relatively rough surface. These rough surfaces increase local turbulence and this may favour the deposition of medium sized particles, due to increased inertial impact (Amoroso and Fassina, 1983). Further to this, the high porosity and coarse texture of many sandstones allows greater infiltration of rain and runoff water. Consequently, water is less

effective at removing particles from the surface of the stone and may carry them further into the pores. Also, the higher infiltration rates cause the surface to remain wet for longer and this favours adhesion of particulates (Sabbioni and Zappia, 1992a).

Not all researchers on sandstone agree with the view, held by Sabbioni and Zappia (1992), that crusts form irrespective of exposure to rain water. Twilley and Podany (1986) note that scaling crusts develop on areas exposed to prolonged water absorption or capillary rise. Black crusts may be patchy on individual buildings, often being related to a local calcium source, such as mortar (Smith *et al.*, 1994). Lofvendahl *et al.* (1992) considers that organic colonisation is heavily dependent on moisture and occurs mainly on the north side or in shaded areas. Observations by Bluck and Porter (1991b), reveal that where excess moisture is supplied to a stone (e. g. horizontal surfaces), the stone stays wet longer and consequently preferential soiling, organic growth and damage, occurs. In contrast, stones protected from moisture have limited crusts or plant growth. Furthermore, Twilley and Podany (1986) note that, slower drying areas develop a different type of crust to faster drying areas. Analysis of these crusts show that feldspar has undergone complete hydrolysis to clay, leaving quartz as the principal detrital material, whereas areas subjected to more rapid drying are hardened by salt recrystallisation (Twilley and Podany, 1986). Wendler *et al.* (1990) observe that facades exposed to sun, wind and driving rain experience rapid wetting and drying, which cause scaling crusts to predominate on these facades. Smith *et al.* (1992) consider that mechanical breakdown occurs where temperature and moisture cycling is frequent and preferably intense, and where salts can accumulate, but still receive moisture. Bernardi *et al.* (1985) comment that deterioration of stone is favoured where wetting-drying cycles are most frequent. Evaporation concentrates the solution, favours salt crystallisation, and increases the pressure of water vapour entrapped inside the stone. Condensation provides water necessary for chemical reactions to occur and increases the deposition of atmospheric particulates on vertical surfaces.

Spatial variability in the deposition of atmospheric particles can result due to variations in the atmospheric conditions (Amoroso and Fassina, 1983; Verheof, 1988). Wet deposition is greatest on stones receiving wind driven rain, while several factors influence rates of dry

deposition, the importance of which depends on particle size. A summary of the main dry deposition mechanisms and the optimum conditions for their operation is presented in Table 2.3.1.

2.3.3 MICRO SCALE

On some walls certain stones weather differently under the same exposure conditions. Smith *et al.* (1994) note that case-hardening occurs predominantly on the most homogeneous stones, as sedimentary structures and clays appear to prevent the formation of a uniform outer layer. However, in contrast, Wendler *et al.* (1990) note that crustal detachment predominates on clay rich sandstones. Bluck and Porter (1991a) observe that the nature and the severity of the crust depends upon the composition and the porosity of the stone (Figure 2.3.1). Spatial variations in weathering within single blocks of stone are commonly reported. These may be due to geological variations or may be visible as alveolar, as discussed in Section 2.2.

2.4 WEATHERING RATES

The expression of average weathering rates based on short term measurements (e.g. Jaynes, 1985) or calculated as surface recession rates, by reference to a datum (e.g. Sharp *et al.*, 1982) has given some useful indications to the weathering rates of limestone. However, due to the cyclic and sporadic nature of sandstone weathering, the potential of these approaches for sandstone is limited (Smith *et al.*, 1994). Consequently, little precise data on the weathering rates of building sandstones exists. However, qualitative observations have been carried out. Fobe *et al.* (1993), note that the surface of a fifteenth century sandstone building in Belgium had retreated by about 10 mm. Geike (1880) notes a good quality sandstone weathers very little in 200 years. Hirschwald (1908) observes that Brochterbeck Sandstone in Germany is in good condition after 100 years, slightly weathered after 550 years and strongly weathered after 900 years. In contrast, Rothenburg Sandstone, shows traces of weathering after 55 years and is strongly weathered after 100 years (Hirschwald, 1908). Although this gives very little idea of the actual surface recession rates it does indicate the variability in the rate of sandstone weathering.

As crust formation is the dominant weathering form affecting most sandstones, the majority of stones experience a succession between times of surface stability (crust formation) and times of catastrophic surface loss (crust detachment) (Smith *et al.*, 1994). Individual stones may occupy different positions in the weathering cycle, making the estimation of weathering rates difficult. Smith *et al.* (1994) point out that in most cases surface loss is related to salt accumulations, building up until a threshold is reached, which causes catastrophic surface detachment. Therefore, as well as indicating present salt accumulation rates, surface loss indicates past environmental conditions.

2.5 SUMMARY

i) The following processes may be involved in gypsum crust formation:

a. Sulphation of calcium carbonate, contained in the stone, with atmospheric SO_X.

b. Sulphation of calcium derived from other materials, such as mortar.

c. Atmospheric deposition of gypsum directly onto the surface of the stone.

d. Activity of bacteria.

ii) Blackening of a crust may be caused by soot, fly ash, organic growth, soil dust, precipitation of iron, and particles from tyres and asphalt.

iii) Development of case hardened crusts occurs due to the deposition of solutes derived from the stone, especially silicon and iron.

iv) Some crusts detach from sandstones with no surface alterations.

v) The following processes may contribute to the detachment of crusts:

a. Lack of cohesion of the material beneath the crust.

b. Moisture trapped under the crust.

c. Salt pressures behind the crust.

d. Expansion and contraction cycles, caused by moisture and temperature changes.

vi) Granular disintegration may occur if salt crystallisation occurs at the surface.

vii) Rapid stone breakdown occurs on detachment of a crust, due to granular disintegration and multiple flaking.

viii) Heterogeneous cementation, and localised patches of certain minerals and clays may cause irregular sandstone weathering.

ix) Evidence suggests that alveolar are related to the effects of salt and not aeolian abrasion.

x) Some evidence suggests that sandstone buildings in urban areas have more black crusts and higher gypsum concentrations, than those in rural areas.

xi) Evidence of the influence of exposure upon the distribution of black crusts is inconclusive. However, the supply of moisture and speed of drying influences the type of crust.

xii) Weathering is most severe where temperature and moisture cycling occurs and salts accumulate.

xii) Sandstone weathering is generally cyclic in nature, with periods of stability followed by catastrophic surface loss.

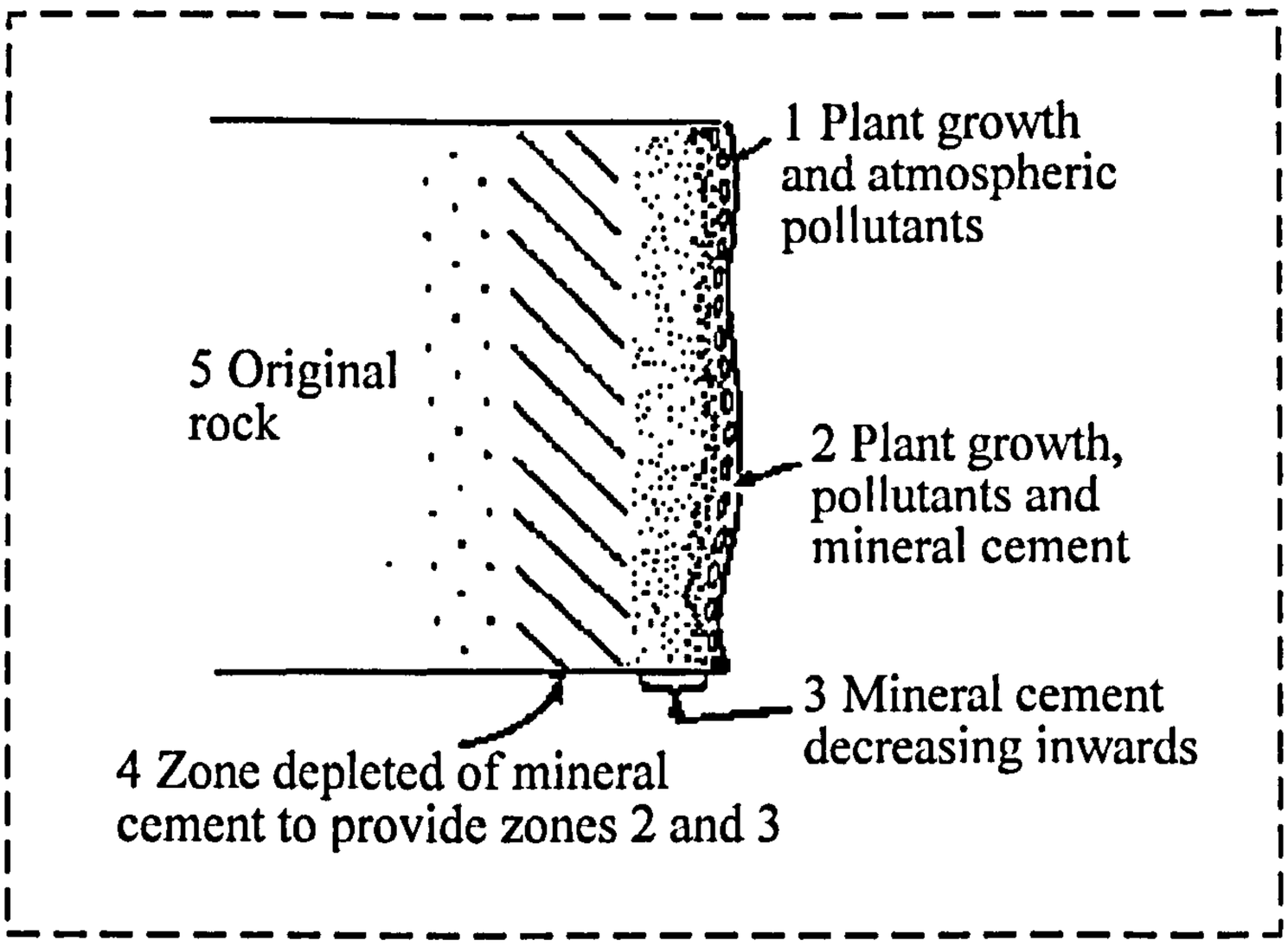

Figure 2.2.1. Crust formation on sandstones in Glasgow (After, Bluck and Porter, 1991b).

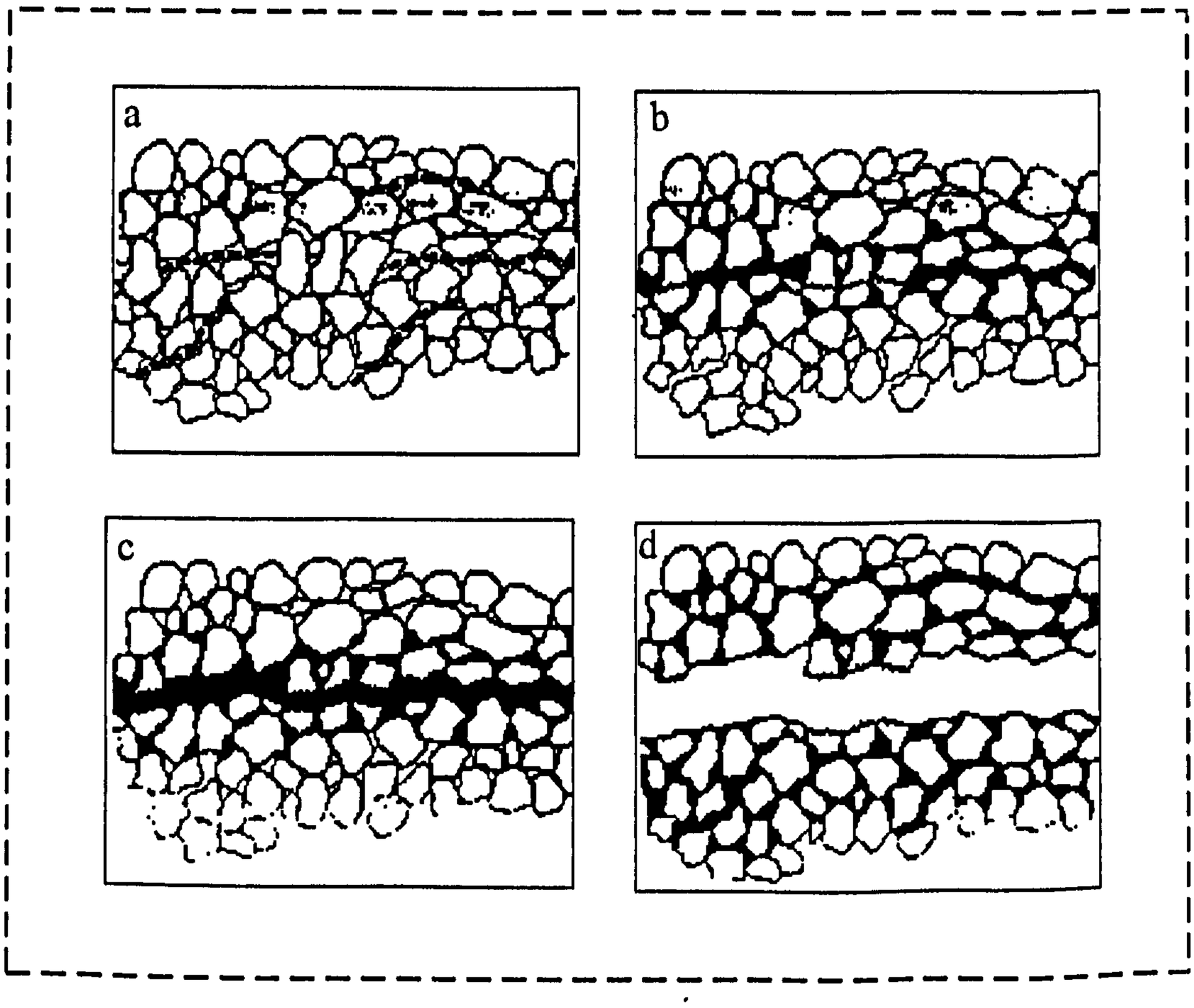

Figure 2.2.2 Sequence of crack formation and development in sandstones. (a) potential cracks. (b) salt crystallisation at a specific depth causes compressive fracturing of grains between potential cracks. (c) beginning of crack exploitation. (d) crustal detachment (After, Smith and McGreevy, 1988).

Dry deposition mechanism	Optimum particle size (μm)	Optimum conditions
Brownian motion	< 0.1	Unaffected by stone inclination and atmospheric conditions
Thermophoresis	< 0.1	Stone colder than surrounding air
Inertial impact	0.5 - 10	Air in motion
Gravitational settling	> 20	Air not in motion
Stefan flow	All sizes	Condensation of water vapour onto the stone

Table 2.3.1 Mechanisms causing dry deposition of atmospheric particles. Information derived from Amoroso and Fassina (1983) and Verheof (1988).

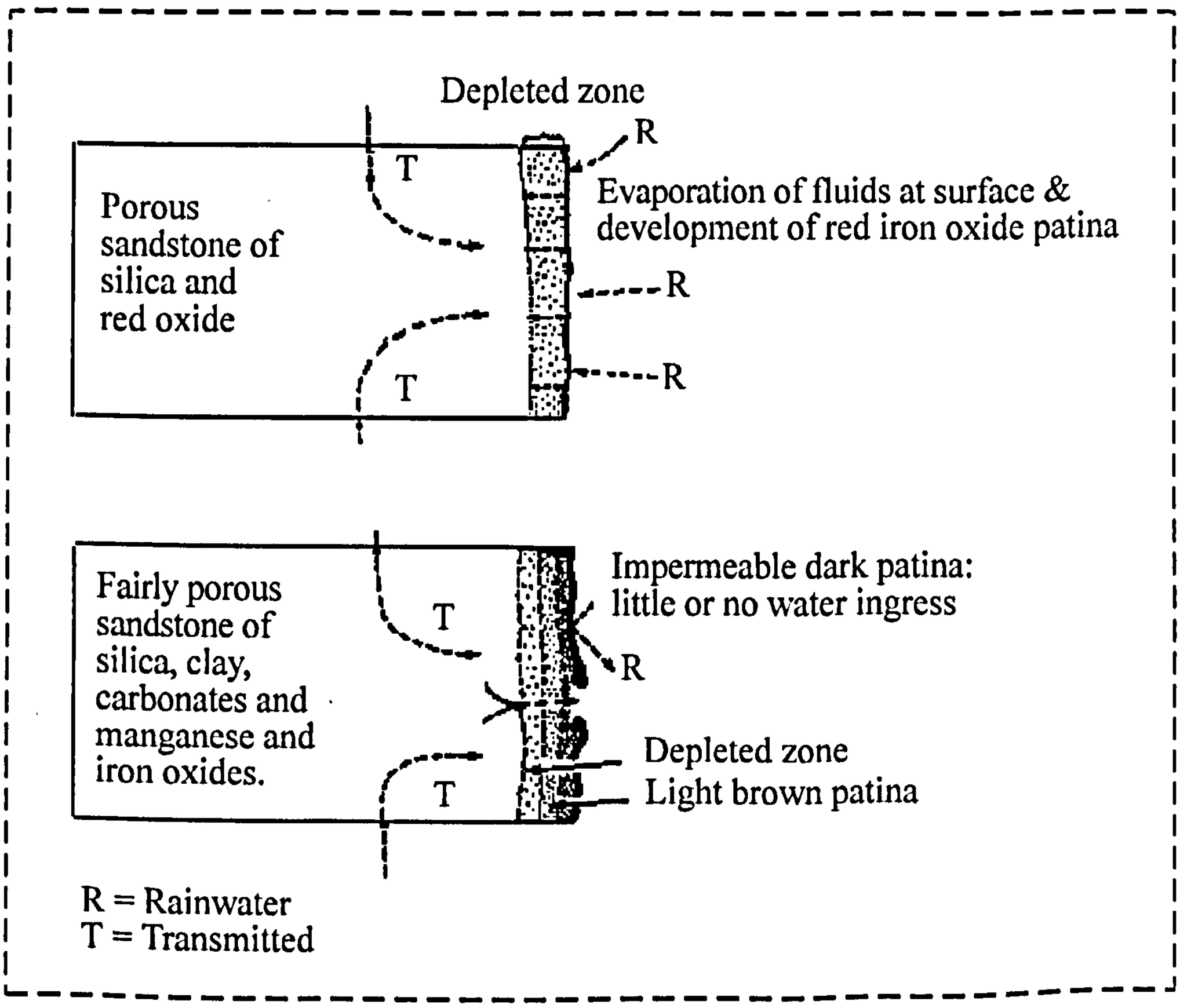

Figure 2.3.1. Crust development on two different sandstones (After, Bluck and Porter, 1991a).

CHAPTER 3

EXPERIMENTAL DESIGN AND STUDY AREA

3.1 INTRODUCTION

As stated in the introduction to this thesis, the objective of this research was to identify and explain the mechanisms and weathering forms responsible for the weathering of sandstone buildings in relation to the environmental conditions of the West Midlands, England. Chapters 1 and 2 have introduced the mechanisms of sandstone weathering and the manifestation of weathering forms on buildings. In this Chapter, the specific aims of the research are formulated and the experimental methodologies required to meet them are introduced. Also, a description of the West Midlands region is presented. This includes historical information about past environmental conditions, as many of the buildings studied in this thesis were built in the 19th century. Further to this, consideration is given to the representativness of the meteorological conditions experienced during the experimental period.

3.2 SELECTION OF SUITABLE RESEARCH METHODOLOGIES

The review of literature concerning the weathering of sandstone buildings, presented in Chapters 1 and 2 leads to the identification of areas of research, which would contribute to the understanding of sandstone weathering mechanisms and forms. Consideration of the relevance of these areas of research to the identification and explanation of the weathering of sandstone buildings in the West Midlands, gives the following four areas of investigation:

1. There is general agreement in the literature that the supply of moisture, especially wetting-drying cycles, is important in sandstone weathering. Also, the role of heating-cooling and freeze-thaw cycles have been suggested as important weathering mechanisms. Monitoring and calculation, of the occurrence and severity of these cycles is lacking. This research aims to measure the frequency and amplitude of these cycles, and investigate their relationship with the severity of sandstone weathering, thereby, determining the importance of these cycles upon the weathering of sandstone buildings.

2. Recent literature emphasises that the chemical weathering of sandstone may be more important than previously thought. This is partly supported by field observations and laboratory studies. However, real time measurements of the chemical weathering of sandstone, especially silica dissolution, under normal exposure conditions are absent. The research aims to measure and asses the importance of chemical weathering, with special reference to environmental conditions.

3. Several forms of weathering, such as crusts and alveolar, have been reported on sandstone. However, quantification of the occurrence of each weathering form is lacking. The research aims to quantify the importance of each weathering form under various environmental conditions in the West Midlands.

4. Evidence to explain the mechanisms that create certain weathering forms is deficient. By quantifying the importance of each weathering form, under various environmental conditions, the research aims to explain the conditions required for their formation and therefore, improve understanding of the mechanisms involved. At the macro scale this involves examining the difference between urban and rural locations. Meso scale influences, such as aspect, will also be examined and at the micro scale the influence of local shelter and height above ground level will be considered.

A review of published literature identifies methodologies which have been applied by researchers to various types of stones, in different environments. In order to meet the above aims, selected techniques have been modified or developed further. Five experiments were designed to meet these aims. Table 3.2.1 demonstrates how these five experiments contribute to the aims of this research. Details of these experiments are presented in Chapters 4 and 5. However, a brief introduction to their principles and historical development will be discussed in this chapter.

The microcatchment technique was developed by Jeffrey *et al.* (1985), on Portland Limestone in Dublin. The technique exposes a slab of stone fitted with a P.V.C. surround and held at an angle fifteen degrees to the horizontal. The bottom corner of the surround

has an outlet to a polyethylene bottle. This enables precipitation falling within the surround to interact with the stone and runoff into the bottle for subsequent chemical analysis. The results from the stone microcatchments are compared to those from a perspex control microcatchment (Jeffrey *et al.*, 1985). Since the development of this unit, there have been many variations in the materials and the dimensions used. For example, Cooper *et al.* (1992), O'Brien *et al.* (1991), Sweevers and Van Grieken (1992) and Halsey *et al.* (1995). However, the principle remains similar. Jeffrey *et al.* (1985) found that this technique yielded sufficient volumes of runoff from limestone and granite. Sweevers and Van Grieken (1992) constructed microcatchments with dolomitic sandstone, granite and marble. Similar in principle to the microcatchment experiments, is the research on the chemistry of runoff water from standing buildings. For example, Roenicke and Roenicke (1972), Livingston *et al.* (1983), Leysen *et al.* (1987), Leysen *et al.* (1989) and Vleugels *et al.* (1992).

Exposure trials, with prepared stone tablets, have been used to evaluate the role of different environmental conditions upon chemical weathering of stone, especially limestone. For example, Jaynes (1985), Inkpen (1989), Whalley, *et al.* (1992) and Moses (1994). The technique involves exposing the tablets for specified periods of time, in different environments. After exposure a measure of the degree of weathering is obtained. This may involve measuring a weight change, alteration of surface roughness, chemical alterations or visual alterations determined by microscopy.

Many climatic variables have been highlighted as being important in stone weathering, but of particular relevance are the temperature and the moisture content of the stone (Ashton and Sereda, 1982). Geomorphologists have considered temperature and moisture changes as potential weathering mechanisms since the early observations of Brown (1924). Since this time many investigations have been conducted into measuring the effectiveness of temperature and moisture changes, as weathering mechanisms (Section 1.2).

Knowledge of stone weathering, gained by sensitive measurement techniques, applied over short periods of time, contribute greatly to our understanding of stone weathering mechanisms. However, to evaluate the occurrence of various weathering forms, it is necessary to carry out objective assessments of weathering features which have formed over

Research aims / Experiments	Thermal and moisture cycles	Chemical weathering of sandstone	Macro scale influences on weathering forms	Meso scale influences on weathering forms	Micro scale influences on weathering forms
Microcatchment measurements		✓			✓
Exposure trial		✓	✓	✓	✓
Temperature and moisture monitoring	✓			✓	✓
Building survey	✓		✓	✓	✓
Analysis of weathered stone		✓	✓	✓	✓

Table 3.2.1. Experiments designed to meet the aims of this research. Ticks indicate which experiments contribute to each aim.

longer periods of time. Previous researchers have used buildings and other dateable rock structures, to examine weathering processes. However, much of the research on the weathering of sandstone buildings is in the form of case studies, which tend to concentrate on single buildings. Less interest has been placed on quantifying the occurrence of different weathering forms and determining the factors responsible for their distribution.

Analysis of weathered stone collected from buildings generally involves determining visual alterations with microscopy or measuring chemical alterations. Chemical alterations may be assessed by the calculation of weathering indices in order to compare the stone to its unweathered state, for example, Sabbioni and Zappia (1992).

3.3 THE STUDY AREA: THE WEST MIDLANDS, ENGLAND.

The majority of research presented in this thesis was conducted in the West Midlands Conurbation or the immediate surrounding areas. Two exceptions are the use of a rural site in Shropshire, 60 km north-west of Wolverhampton, for the exposure trial and Lichfield Cathedral in Staffordshire, 35 km north-east of Wolverhampton, for monitoring temperature and moisture cycles (Figure 3.3.1). These two sites will be described in more detail in Chapters 4 and 5. As most of the research presented in this thesis is concerned with the conurbation and surrounding area, a brief description of this area is provided below, to illustrate the general environmental conditions. It is also appropriate to introduce the history of the area, as the building survey examines stones that have been exposed since the beginning of the 19th century (Chapter 4). Therefore, an introduction to the industrial development and air pollution history of the area is presented so that alterations to the weathering environment can be understood.

3.3.1 POPULATION, INDUSTRY AND ATMOSPHERIC POLLUTION IN THE NINETEENTH AND TWENTIETH CENTURIES

Close to the centre of the West Midlands Conurbation is an area known as the Black Country. The name is derived from the heavy industry that was once characteristic of this area, notably the mining of coal, ironstone and clay, and dependent industries (Allen, 1946). The industry of the Black Country facilitated the growth of Birmingham and the

surrounding area, to form the West Midlands Conurbation. The Black Country is an economic and social unit, with no physical features that act as boundaries. It runs from Short Heath to Bloxwich and Walsall to north west Wolverhampton to Wordsley, to Stourbridge and Halesowen (Allen, 1929).

The Black Country experienced rapid growth from 1785-1860 and established itself as a hardware centre. The growth of the area is demonstrated by the population experiencing more than a four fold increase in the sixty years between 1801 and 1861 (Table 3.3.1). In 1860 the outputs from the area were mostly iron mongery, as the local raw materials were coal and ironstone, which were produced in huge quantities (Table 3.3.2). All staple manufactures relied on these materials and one third of British finished iron was produced in the Black Country. From 1861-1885 growth was slow, as existing economies experienced depression and industry adjusted to new markets. From 1886 to 1927 the new engineering based firms experienced rapid growth, while the traditional industry slowly declined. By 1910 coal production had declined and iron was outdated by steel (Table 3.3.2), however at this time the cycle and motor industry developed, along with allied trades, such as tyre, electrical, chemical and paint manufacturing. Manufacturing remained very important in the conurbation into the 1970's with motor manufacture dominating (Warren Spring Laboratory, 1973). Today however, manufacturing industries have declined greatly and are now much less important than in previous decades.

The history of heavy industry in the West Midlands Conurbation has obviously caused the severity and nature of atmospheric pollution to vary over the 19th and 20th centuries. Some information on the severity of pollution can be gained from historical documents. In 1850 the dense smoke of the West Midlands was noted as blackening and obscuring everything around (Pickwick Papers, cited in, The West Midlands Group, 1948). In 1948 the harmful effects of smoke to humanity, buildings and vegetation was noted (The West Midlands Group, 1948). At this time it was calculated that 5.4% of the weight of coal burnt in ordinary open fires escaped into the air and this consisted of 2.7% soot and tar, 2.4% sulphur dioxide and 0.3% ash (Heating and Ventilation Committee of the Building Research Board, 1945). More precise information can be obtained from a period of air

pollution monitoring between 1939-1944. This suggests that the quantity of pollution varied from place to place within the conurbation (Table 3.3.3), with ash being deposited close to its source, while smoke and sulphur oxides were transported greater distances (The West Midlands Group, 1948). It can be seen that the levels of pollution in central Birmingham were similar to those in central London for the same period (Table 3.3.3). In 1956 the Clean Air Act was introduced and smoke control areas were established in the conurbation. These areas were quite extensive by the 1970s, but were concentrated around the perimeter of the conurbation, and much of the central area and the Black Country remained without smoke control. Most areas of the conurbation received a 60% decrease in smoke concentrations during the 1960s (Warren Spring Laboratory, 1973). There was also a general reduction in sulphur dioxide, but this was not as great or as widespread as the reduction in smoke (Warren Spring Laboratory, 1973).

3.3.2 PHYSICAL SETTING

The West Midlands region is surrounded by rising ground, with the Pennines to the north, the Northampton Uplands to the east, the Cotswolds to the south and the Welsh Mountains to the west. In the centre of this region, the West Midlands Conurbation is situated on a plateau, which extends from Cannock Chase, in the north, to the Forest of Arden, in the south. Most of the area is below the 150 m contour, with the exception of the occasional outcrop of higher ground.

The geology of the West Midlands region was very important for supplying the raw materials necessary for the industrial development of the region, as well as supplying sandstone for building purposes. Most of the Black Country was developed on Carboniferous Coal Measures (Figure 3.3.2). To the north of the Black Country is the Great Bentley Fault, just north of Walsall. North of this fault the coal seams are separated by sandstones and shales. To the east, the coal terminates in a fault running from Quinton to north east of Walsall. To the east of this fault is the Permian Red Sandstone, such as that seen at West Bromwich. To the east of the Permian Sandstone is the Triassic Sandstone. To the south of the Black Country the coal is terminated by the Permian Red Sandstone of the Clent Hills. To the west, the coal measures meet the Permian Red Sandstones of the

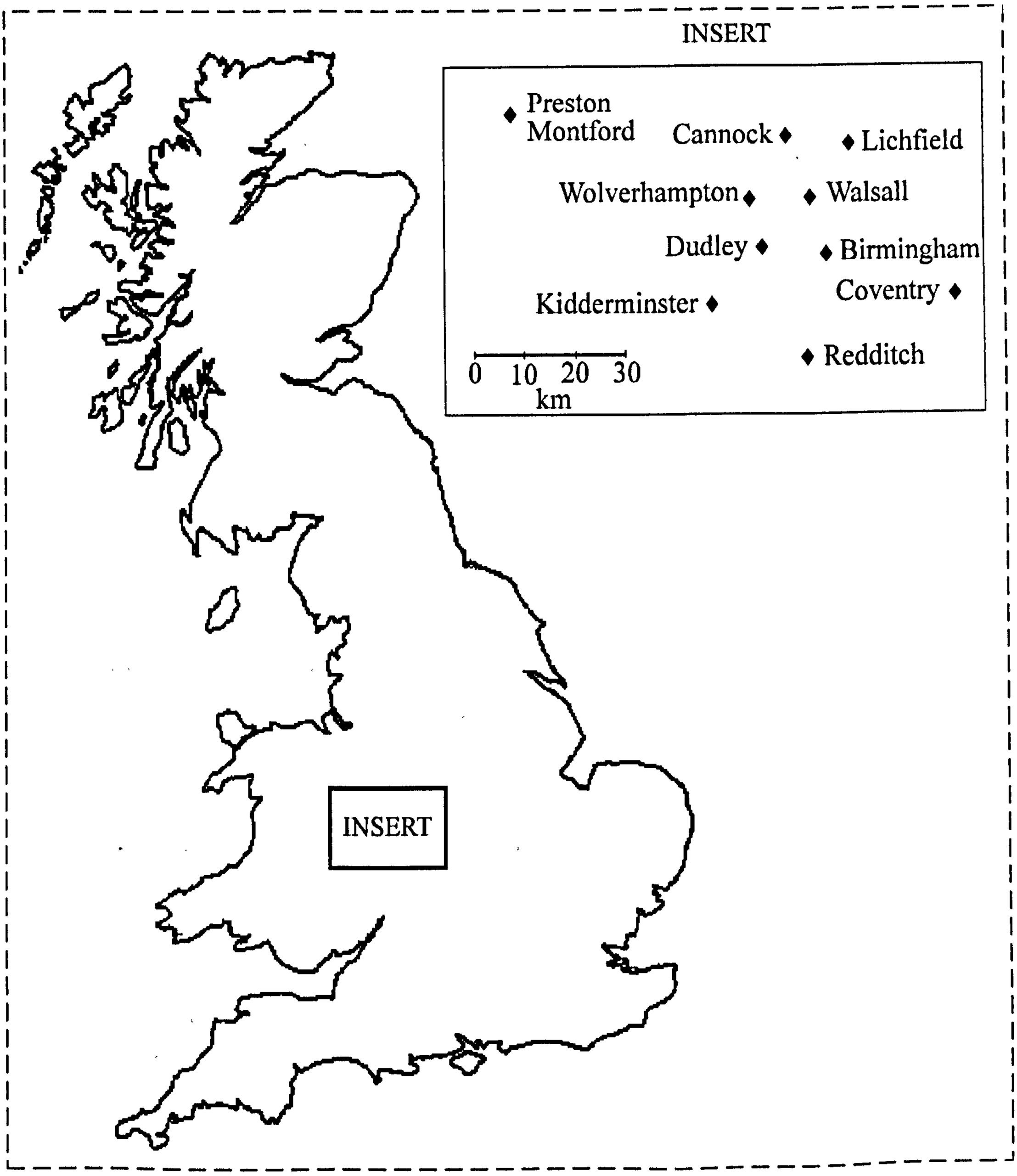

Figure 3.3.1 Location of the study area.

Year	Population
1801	187,000
1861	800,000
1921	1,855,000
1973	2,500,000*

Table 3.3.1 The population of Birmingham and the Black country (After, Allen, 1929.

* population of the Conurbation, after, Warren Spring Laboratory, 1973).

Year	Coal Production (million tons)	Ironstone Production (thousand tons)
1865	9	660
1872	9	640
1887	6	110
1900	5	50
1913	3	30

Table 3.3.2 Coal and Ironstone production in the Black Country (After, Allen, 1929).

Recording Station	Soluble matter (lime, chlorides, sulphates)	Insoluble matter (tar, carbonates, ash)	Total
Birmingham, Gt. Charles St.	93.79	203.03	296.82
Birmingham, Bournville	63.49	63.10	126.59
Bilston	84.76	192.17	276.93
Walsall, Goscote Hospital	80.32	75.31	155.63
London, Battersea Park	84.23	198.44	282.67

Table 3.3.3 Annual rate of deposition of air pollution. Figures are yearly averages in tons per square mile for the period 1939-1944, except for Bilston which is for one year (After, The West Midlands Group, 1948).

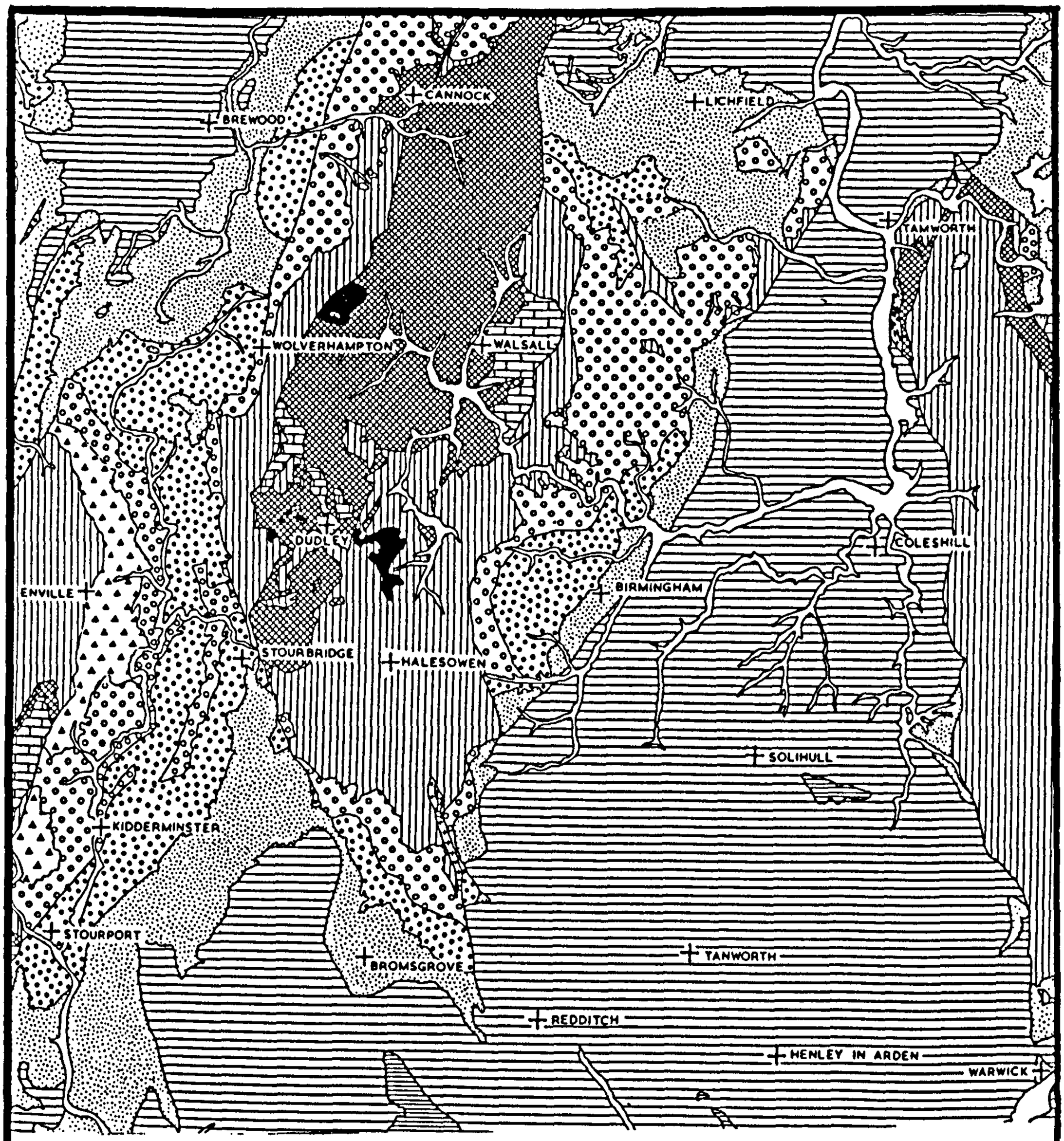

Figure 3.3.2 Solid geology of the Birmingham district (After, Wills 1970).

Wolverhampton area, which eventually give way to the Triassic Red Sandstones of the Tettenhall, Kingwindford and Stourbridge areas.

3.4 METEOROLOGICAL CONDITIONS DURING THE EXPERIMENTAL PERIOD

The experiments used in this research were conducted in a period of 22 months. When evaluating the results from these experiments, it is necessary to consider if meteorological conditions were representative of average conditions. Analysis of meteorological data, collected from Elmdon Airport, Birmingham (Table 3.4.1), shows that during the experimental period, temperatures were typically higher than average, with maximum and minimum temperatures being above average for 16 and 17 months, respectively. The winter of 1994/95 was exceptionally warm. The hours of sunshine were also high, with 18 months having higher than average values. Rainfall was higher than average for 13 of the 22 months. Winter months experienced higher than average rainfall, while rainfall during summer months was lower than average.

3.5 SUMMARY

i) The aims of the research are:

a. Determine the importance of wetting-drying, heating-cooling and freeze-thaw cycles in sandstone weathering.

b. Determine the importance of chemical weathering upon sandstone and identify environmental conditions that support it.

c. Quantify the occurrence of each weathering form under the different environmental conditions of the West Midlands.

d. Evaluate the mechanisms that create certain weathering forms and evaluate the influence of environmental conditions at the micro, meso and macro scales.

ii) The aims of the research will be met by using the following experiments:

a. Microcatchment experiment.

b. Exposure trial.

c. Temperature and moisture monitoring.

d. Buildings survey.

e. Analysis of weathered stone.

iii) The West Midlands Conurbation developed as a result of heavy industry in the 19th century. During this time air pollution was noted as being responsible for damage to buildings.

iv) In the 20th century, engineering was very important up to the 1980's. Atmospheric pollution at this time was comparable to that of London, but did decrease due to the introduction of the 1956 Clean Air Act.

v) The West Midlands is situated on a plateau, with Carboniferous Coal close to the centre and New Red Sandstone at the periphery.

vi) The experimental period was generally warmer and sunnier than average, with wetter than average winters, but drier than average summers.

Month	Maximum daily temperature		Minimum daily temperature		Total sunshine		Total rainfall	
	Mean (°C)	Diff. from 1951-1980 average	Mean (°C)	Diff. from 1951-1980 average	Hours per month	% of 1951-1980 average	mm per month	% of 1951-1980 average
10.93	11.3	-2.6	4.2	-1.9	113	119	74	142
11.93	7.1	-2.1	1.6	-1.3	48	77	72	116
12.93	8.0	0.9	2.2	0.8	62	135	101	155
1.94	8.1	2.2	2.2	1.9	81	172	72	124
2.94	5.9	-0.4	-0.3	-0.5	62	105	59	120
3.94	11.3	2.3	4.2	2.8	125	121	73	143
4.94	12.0	0.1	4.0	0.7	191	118	58	132
5.94	14.2	-1.3	6.4	0.3	145	79	50	89
6.94	19.6	0.7	9.9	0.9	237	122	23	43
7.94	21.1	0.5	11.8	0.7	212	127	26	55
8.94	20.3	0.3	11.3	0.5	191	118	48	67
9.94	16.1	-1.4	9.0	0.2	114	88	113	202
10.94	13.7	-0.2	5.5	-0.6	117	123	62	119
11.94	12.3	3.1	6.5	3.6	46	74	63	102
12.94	9.5	2.4	2.5	1.1	63	137	116	178
1.95	7.7	1.8	1.1	0.8	56	119	105	181
2.95	9.5	3.2	2.9	2.7	77	131	64	131
3.95	9.4	0.4	0.8	-0.6	165	160	50	98
4.95	13.7	1.8	4.1	0.8	191	140	13	30
5.95	16.8	1.5	6.3	0.3	208	117	36	65
6.95	19.3	0.5	9.7	0.5	214	115	9	16
7.95	24.5	3.9	12.7	1.6	252	139	23	49
Mean	NA	0.8	NA	0.7	NA	120	NA	107

Table 3.4.1 Meteorological conditions during the experimental period and a comparison to the 1951-1980 average. Recorded at Elmdon Airport, Birmingham, situated 98 metres above sea level, approximately 15 km east-south-east of Birmingham city centre. Data taken from the Royal Meteorological Society's Weather Logs, October 1993 to July 1995.

CHAPTER 4

MONITORING AND RECORDING WEATHERING ON SANDSTONE BUILDINGS

As detailed in Section 3.2, five experiments were selected to analyse the occurrence and importance of different sandstone weathering mechanisms and forms, in the West Midlands. In this chapter, experiments based on measuring and monitoring sandstone buildings will be considered. These involve the monitoring of stone temperatures and moisture contents, at Lichfield Cathedral, and a building survey to analyse the occurrence of weathering forms on selected buildings. The microcatchment experiment, exposure trial and analysis of weathered stone will be discussed in Chapter 5.

4.1 METHODOLOGY

4.1.1 MONITORING SANDSTONE TEMPERATURES AND MOISTURE CONTENTS

The monitoring equipment consisted of a 'Unidata Model 6004 Data Logger' (Plate 4.1.1), four steel sheathed thermistor probes and four 'Vaisala HMP 35A Relative Humidity Probes' (Plate 4.1.2). The equipment was installed 37 metres above ground level, on the Central Tower of Lichfield Cathedral (NGR SK116098). The majority of the Cathedral was constructed in the 13th from ferruginous sandstones (Plate 4.1.3).

One thermistor and one relative humidity (RH) probe were positioned in each wall of the tower in January 1994 and June 1994, respectively. This gave four highly exposed positions with the orientations north, east, south and west. When positioning the sensors, attention was paid to maintaining geological and exposure similarities between the four walls. In each case, the thermistors (4 mm diameter) were inserted into the stone parallel to the exposed face, but 5 mm from the surface (Plate 4.1.2 and Figure 4.1.1). The thermistors were held in place with 'RS Thermally Conductive Adhesive', which ensured a good thermal contact between the sensor and the stone. In this study the use of thermistors at a 5 mm depth was thought to be preferable to disrupting the stones surface with surface mounted thermistors. Warke and Smith (1994) report a temperature gradient of $0.6^{o}C\ cm^{-1}$ between the surface and 25 mm depth for Dunhouse Sandstone with a surface

temperature of 36°C. This suggests that measurements at 5 mm depth will be very similar to those obtained with surface mounted thermistors. To check this surface temperatures were measured with an infrared thermometer at the start of the experiment (Appendix 10).

The RH probes (25 mm diameter) were inserted by drilling a 25 mm deep hole in the exposed face of the stone. The sensing part of the probe (the last 25 mm) was inserted and an air tight seal created with silicon sealant (Plate 4.1.2 and Figure 4.1.1). Therefore, the humidity reading represents the RH of a pocket of air trapped beneath the surface of the stone to a depth of 25 mm. Fassina and Stevan (1992) used Vaisala RH probes in a similar way to monitor interior wall moisture levels.

The data logger was initially programmed to take maximum, minimum, average and raw temperature readings, to the nearest 0.1°C every five minutes, but analysis of the data showed that temperature changes were not highly variable so the datalogger was re-programmed to take a raw reading every fifteen minutes. Relative humidity was recorded to the nearest per cent and again raw readings every fifteen minutes were found to be sufficient. The data logger could run continuously for about six months, but it was generally down loaded monthly in case of damage or malfunction. Several problems arose with the equipment over the course of the monitoring period, which resulted in the loss of some data. The most difficult problem was caused by the RH sensors getting wet when water infiltrated into the cavity housing the RH probe, dripping through the protective membrane onto the sensor. This only occurred in very heavy or prolonged rainfall, but it artificially extended the length of time taken for any drying of the stone to be recorded. From examination of the data, it was possible to find the times when this fault occurred, allowing the fault to be considered in the analysis.

The logger was down loaded with a portable computer and the data imported into Microsoft Excel for initial analysis. The raw data was analysed with descriptive statistics and One-Way Analysis of Variance (ANOVA) (Appendix 1). Several factors, considered to be important to weathering, were calculated using mathematical and logic functions in Microsoft Excel (Table 4.1.1).

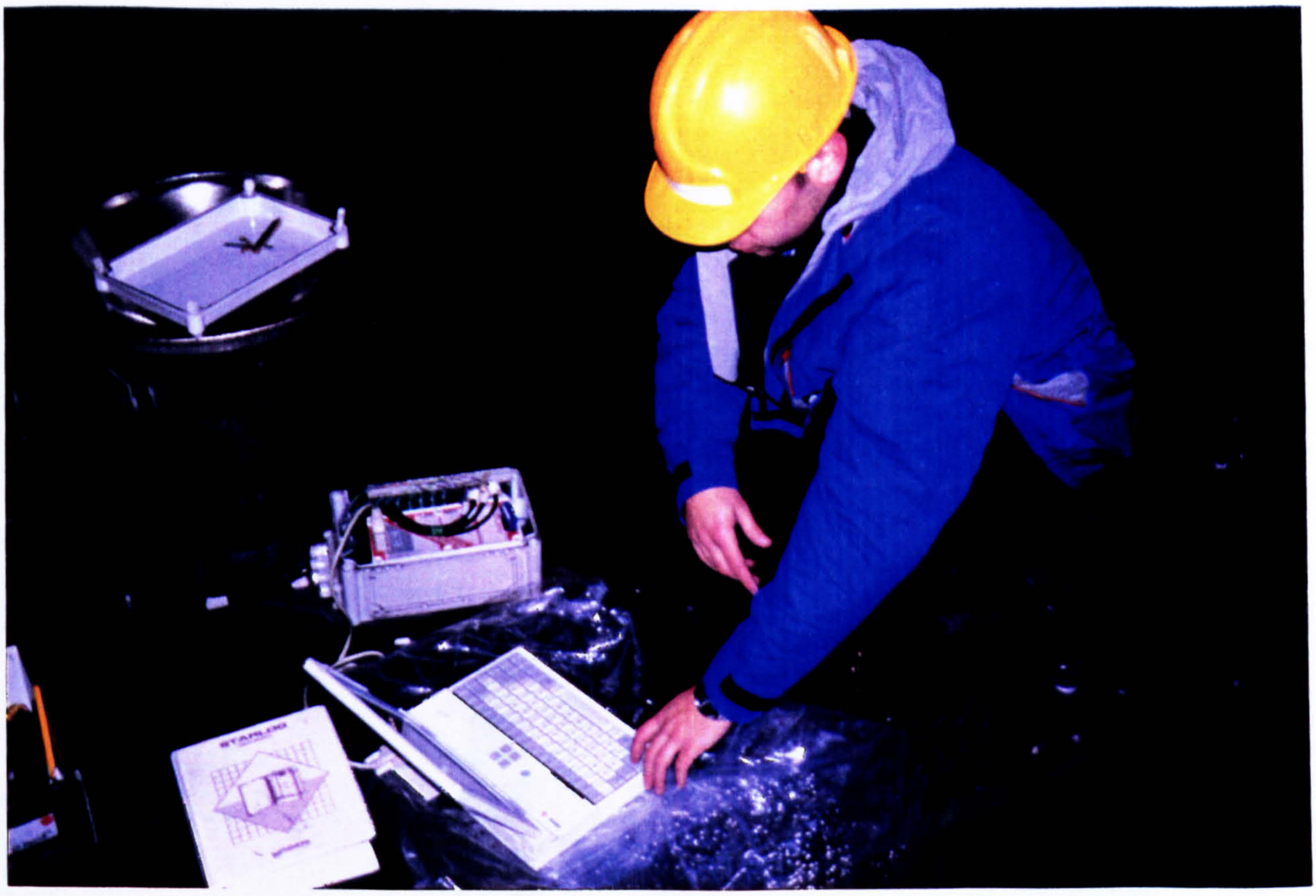

Plate 4.1.1 Data logger installed inside the Central Tower of Lichfield Cathedral. The logger is being down loaded with a portable computer.

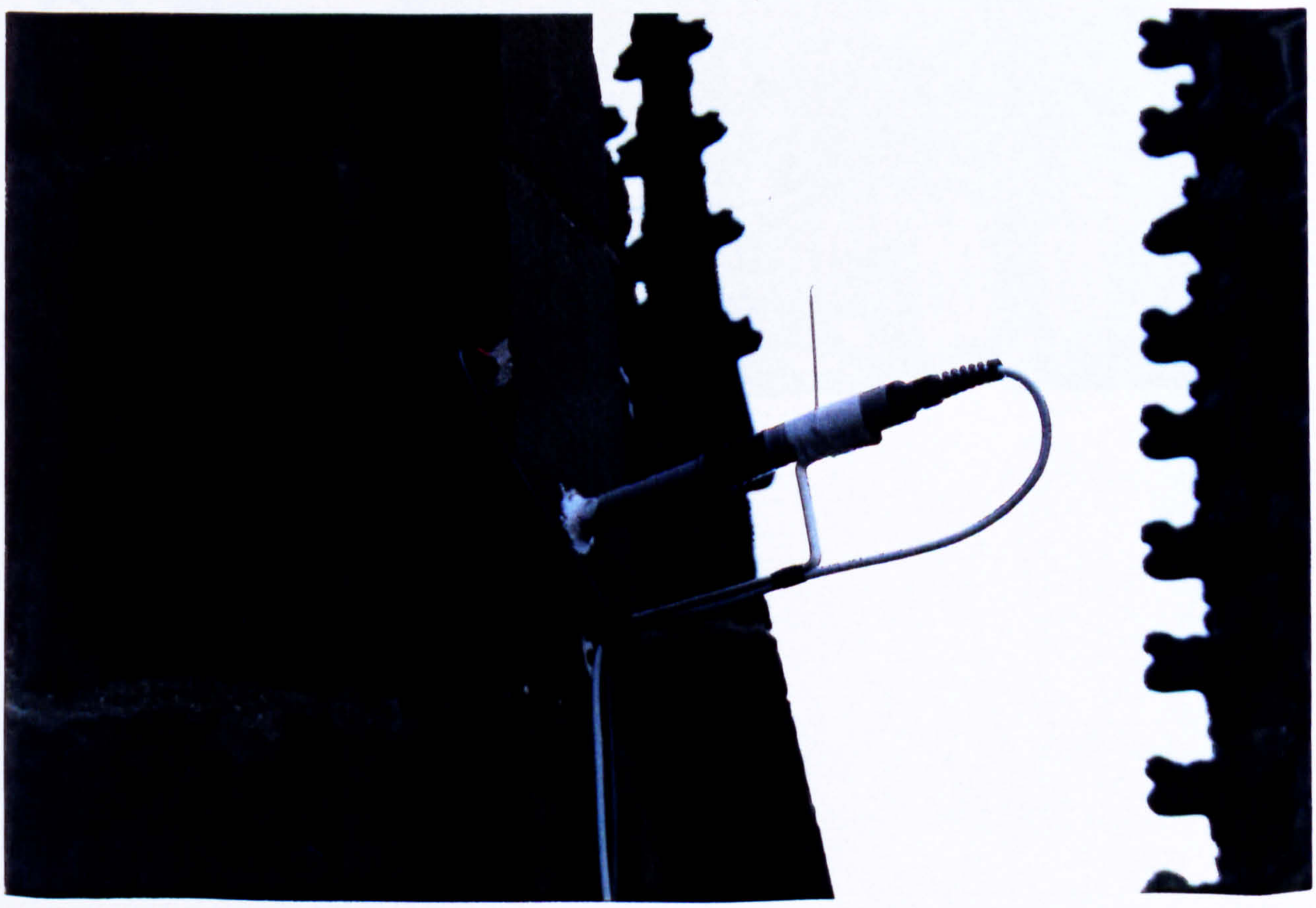

Plate 4.1.2. Thermistor and relative humidity probe in place on the Central Tower of Lichfield Cathedral.

Plate 4.1.3. General view of Lichfield Cathedral.

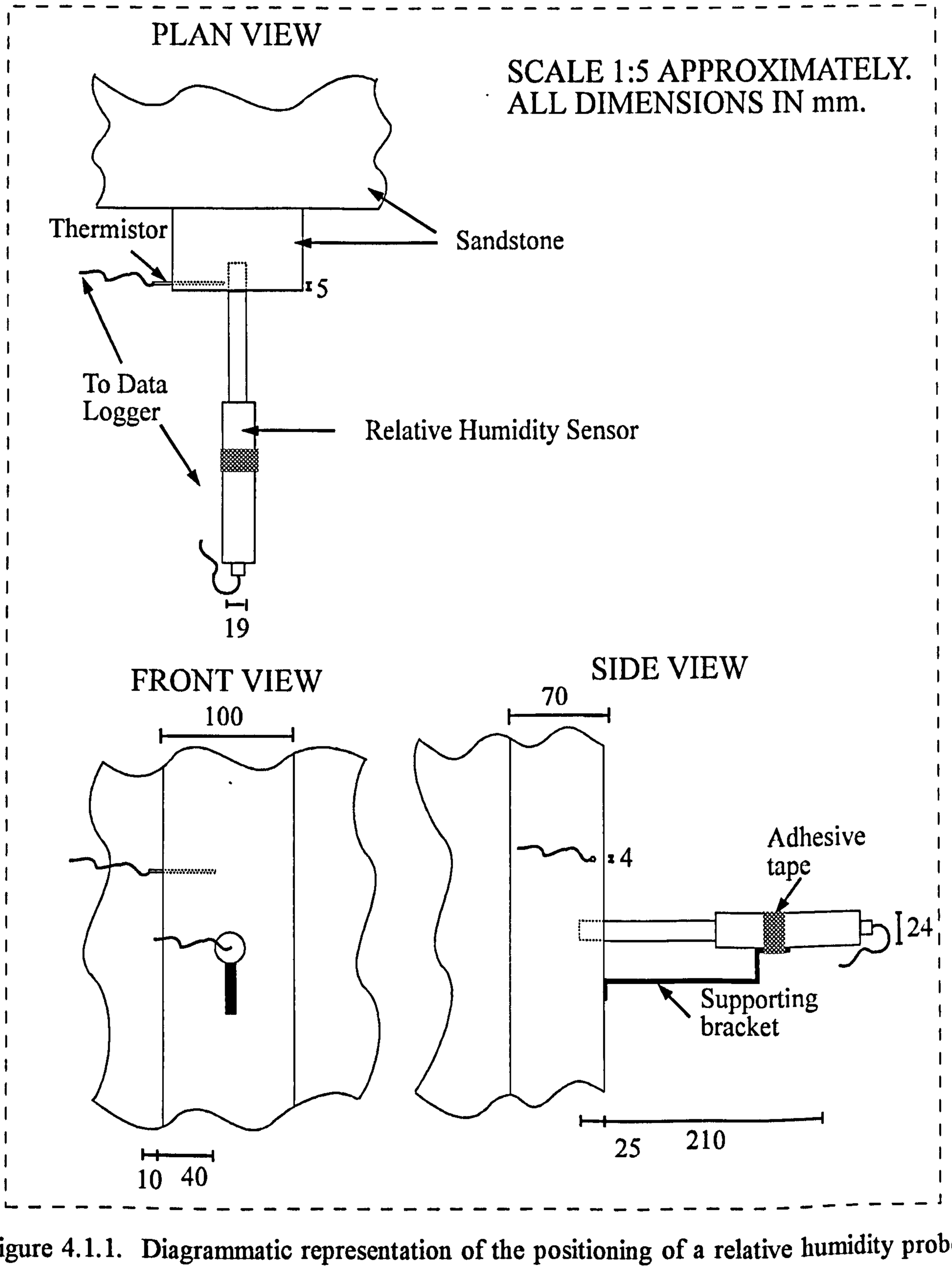

Figure 4.1.1. Diagrammatic representation of the positioning of a relative humidity probe and thermistor at Lichfield Cathedral.

Factor	Description
Rates of temperature change (monthly mean, maximum and minimum)	Temperature changes per fifteen minutes.
Rapid heating and cooling (number month^{-1})	The number of times heating and cooling rates exceed 1^{o}C in fifteen minutes.
Heating-cooling cycles (number month^{-1})	Cycles consist of temperatures increasing and then decreasing. When temperatures start to rise again a new cycle begins. For an increase or decrease to be registered the mean rate of temperature change must be >1^{o}C hr^{-1}
Rates of relative humidity change (monthly mean, maximum and minimum)	Relative humidity changes per fifteen minutes.
Wetting-drying cycles (number month^{-1})	Cycles consist of relative humidity increasing and then decreasing. When relative humidity starts to rise again a new cycle begins. For an increase or decrease to be registered the mean rate of change must be >1% hr^{-1}.
Wet-dry cycles (number month^{-1})	A cycle starts when relative humidity is greater than or equal to 80%. When RH falls below 80% one cycle has occurred.*
Time of wetness (minutes month^{-1})	The length of time relative humidity is greater than or equal to 80%.*
Freeze-thaw cycles (number month^{-1})	Freezing occurs when relative humidity is greater than or equal to 80% and temperature is less than or equal to 0^{o}C. A cycle is a period of freezing followed by a thaw caused by a rise in temperature.*

Table 4.1.1 Factors calculated using temperature and relative humidity data, and their descriptions. * To calculate these factors it is assumed that when the sandstone RH is greater than or equal to 80%, moisture is present in the stone. This is based on the findings by Sereda (1974), which show at inland locations plastic and metal surfaces were wet at a RH close to 80%. This assumption has also been used to measure the time of wetness by Henriksen *et al.* (1993).

4.1.2 SANDSTONE BUILDING SURVEY

4.1.2.1 Selection of Buildings

The building survey was carried out in a 700 km^2 area, centred on the West Midlands (NGR SP 010890) (Figure 4.1.2). Two ten kilometre wide transects, forty kilometres long were devised, one ran latitudinally and the other longitudinally. The two transects were selected to incorporate urban and rural environments, and from initial examination of large scale maps and some local knowledge the transects were estimated to be of an adequate size to obtain sufficient suitable buildings to survey. Churches were chosen for the comparative survey as they are easily located, tend to be free standing and, in the West Midlands, many were built of ferruginous sandstone in the 19th century. Therefore, they are of a comparable age and built in a similar architectural style. Also, altars have traditionally been located in the east of the buildings so churches have walls facing north, east, south and west.

The lithology of the sandstone used to build the selected churches was considered, because the properties of the stone play a key factor in weathering, termed 'rock control' (Yatsu, 1966). Rock control theory is concerned with the influence of rock properties upon landform development and geomorphological processes, and has therefore, been considered for many years. When examining the role of environmental conditions upon sandstone weathering, it is desirable to reduce rock control. This can be achieved by classifying the sandstone used for the buildings. The use of a standard geological classification was limited because it is difficult to carry out accurate identification, unless a freshly fractured surface is available. This is rarely possible for a stone incorporated into an historic building. The stone industry classifies building sandstones by reference to the material cementing the grains of stone together (Table 4.1.2). This classification has some relevance to weathering because, in many cases, the cement of the sandstone greatly affects the weathering mechanisms. Therefore, a classification based on the cementing of the stone was used in this survey.

Ferruginous cemented sandstones were the most abundant in the survey area, therefore they were used as the basis of this survey. The definition of ferruginous sandstone is somewhat ambiguous. Fay (1920) claims ferruginous sandstones are 'sandstones rich in

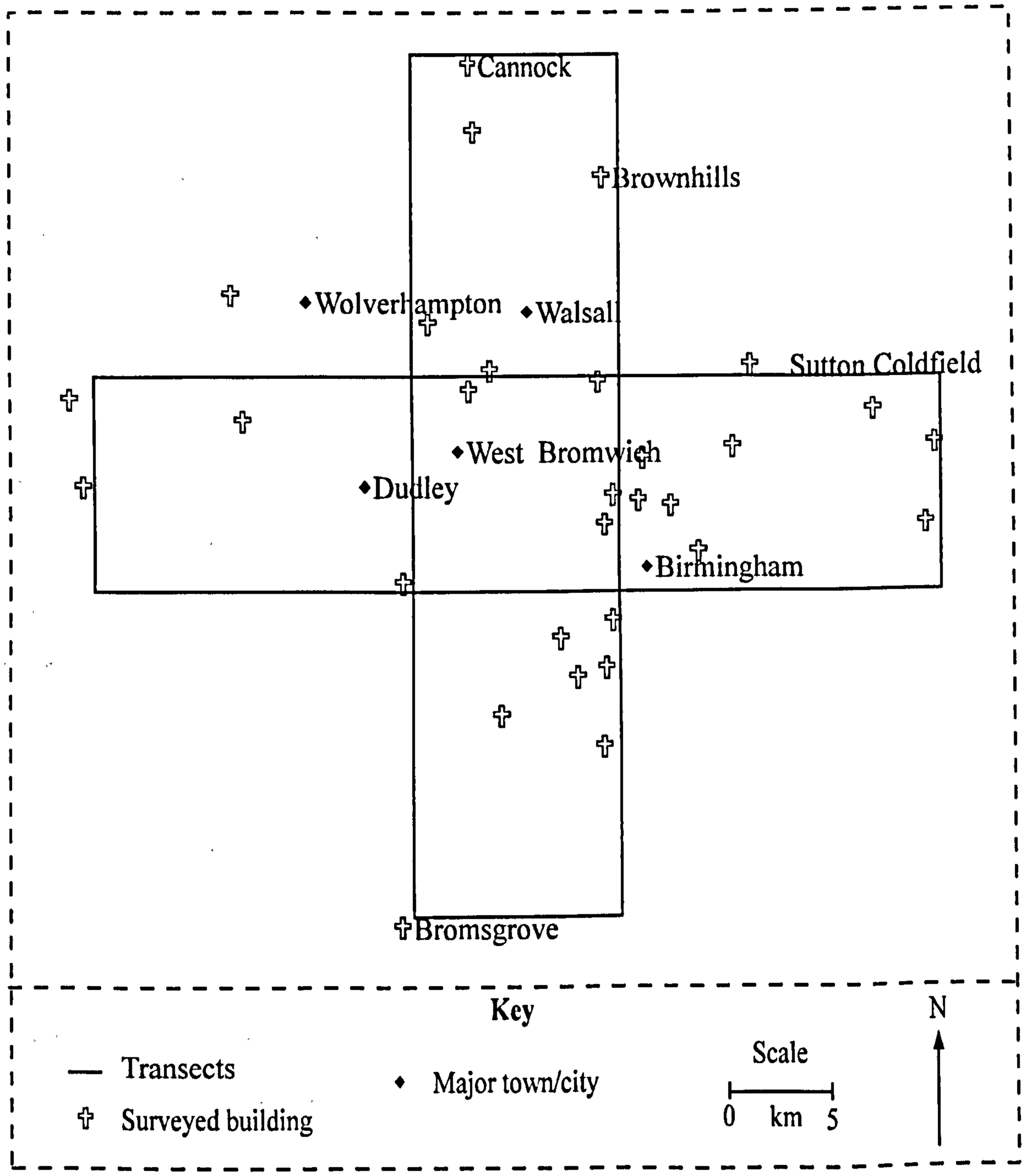

Figure 4.1.2. Survey area and building locations.

Cement	Major component of the cement
Siliceous	Secondarily deposited silica
Calcareous	Calcium carbonate
Dolomitic	Calcium - magnesium carbonate
Ferruginous	Iron oxides
Argillaceous	Clay minerals

Table 4.1.2 The nature of sandstone cementing material (After, Leary, 1986).

iron as the cement material or as grains or both'. An alternative definition of ferruginous stone is 'rocks having a red colour, but not necessarily an abnormally high iron content' (American Geological Institute, 1960). Many sandstones are cemented by iron compounds, but their colour depends on the type of iron compound present. The red iron oxide, hematite, is the most common in the West Midlands area. Therefore, by selecting red/brown (ferruginous) sandstones, the cement is largely hematite, but other cements may be present. However, stones which are cemented largely by other minerals are excluded from the survey. Sandstones with pure calcareous and dolomitic cements tend to be white to buff in colour and are susceptible to weathering by dissolution of the cement. Siliceous sandstones tend to be light grey and are relatively resistant to dissolution. Furthermore, examining sandstones which all have a similar colour is important as the colour of the stone influences the absorption of solar radiation, hence the severity of any insolation weathering. Further to this, differences in stone colour between buildings may cause inconsistencies when conducting a visual assessment of weathering forms.

In order to select the buildings suitable for surveying, all the churches in the survey area were visited. Buildings constructed from ferruginous sandstone were noted and details of their age, architecture, maintenance and location, recorded. This enabled the selection of the most suitable buildings for subsequent surveying. Cleaned or heavily restored buildings were excluded, leaving twenty four 19th century churches. Six churches built as early as the 12th century were also included in order to gain a more even distribution in the survey area. This gave a total of thirty buildings (Figure 4.1.2 and Table 4.1.3).

4.1.2.2 Differentiation of Weathering Forms

In order to record the type and severity of weathering it was necessary to devise a system to classify the different forms of weathering. Lofvendahl, R *et al.* (1992) initiated an inventory of weathering, with eight major weathering forms, on sculptured stone in Sweden, which was itself a simplification of the classification system of Fitzner and Kowatski (1990). The system by Fitzner and Kowatski (1990) is very extensive with approximately forty weathering forms and a host of criteria which are difficult to define. The system used in this research was modified from Fitzner and Kowatski (1990), reducing the classification to

eighteen forms of weathering (Table 4.1.4). These were selected by simplifying the classification, removing criteria which were difficult to define and removing weathering forms inappropriate to sandstone.

4.1.2.3 Survey Technique

Various methodologies for recording the weathering forms demonstrated by a building or rock outcrop have been proposed, but they can generally be classified into two broad categories. The first method, visual representation of weathering, utilises an architectural drawing or photogrammetric picture of the building under study. The weathering forms are classified and a code or colour attributed to each category. This is superimposed onto the image of the building to give a visual representation of the weathering and its distribution. The second method, numeric representation, relies on categorising the type and severity of weathering and assigning a numerical value. With the latter, the data can then be used to give a statistical evaluation of weathering.

The two techniques have distinct features that make them suited to different applications. Visual representation tends to be very time consuming, due to the need of a good quality picture. The results are very accurate, but are difficult to interpret. This technique is better suited to the long term monitoring of weathering on individual buildings, where the survey is repeated at appropriate time intervals. The second method is much more rapid, but it lacks accurate repeatability if it is to be used for monitoring purposes. Numerical representation is suited to a one off assessment of the degree of weathering, since results from the survey are much easier to interpret and make comparisons between buildings.

The survey technique used in this research was designed to give a numerical representation of the weathering forms and their distribution, hence enabling statistical analysis of the data. For each wall of the building a data recording sheet was completed, 'Sheet 1' (Figure 4.1.3). This recorded the basic data for each wall and the surrounding environment. Most of the detail on Sheet 1 is self explanatory. Building code and wall code are simply codes to identify each building and wall when analysing the data. The type of walls were classified as either ashlar or rubble. Ashlar walls are constructed from straight sawn blocks, whereas

rubble walls are constructed from uneven fractured blocks. The type of stone finish, either smooth or rough, was also recorded. Smooth stones have a sawn face, while rough stones have a fractured or carved finish. The variables in italics on Sheet 1 were included to enable the calculation of wind driven rain using BS 8104:1992, as shown in Table 4.1.5.

Once Sheet 1 was completed the weathering of the wall was assessed by completing Sheet 2 (Figure 4.1.4). This was achieved by examining 1 m^2 quadrats of sandstone at heights of 0.2-1.2 m and 1.2-2.2 m every 2 m along the wall (Plate 4.1.4). These heights were selected so that the lower of the two quadrats would represent stone influenced by the capillary rise of water, while the upper quadrat was not so influenced. One quadrat every 2 m along the wall was found to be sufficient to account for the variation shown on most walls. The survey concentrated mostly on vertical walls, but if horizontal or sloped surfaces were present, then their weathering was recorded and for the purpose of this research they were considered as sills. At each height, the distance of the nearest obstruction was recorded and the weathering demonstrated by the wall and any sills recorded. This was done by recording the percentage of cover of the weathering forms to the nearest five per cent. In addition to these weathering forms seven weathering types were also considered (Table 4.1.6). Weathering forms are a morphological feature resulting from weathering, such as black flaking. Weathering types are the sum of related weathering forms. For example, total flaking is the sum of black flaking, autotrophic flaking and case hardened flaking. The variables in italics on Sheet 2 were included to enable the calculation of wind driven rain using BS 8104:1992, as shown in Table 4.1.5.

Name	Location	Building code	Year of construction	Grid reference
St. Michael	Handsworth	C1	1862	SP053872
St. Margaret	Great Barr	C2	1860-1	SP058938
St. Batholomew	Wednesbury	C3	1827 & 1890	SO987934
St. Mary	Handsworth	C4	1876-80	SP056884
St. John Baptist	Lea Marston	E1	1876-7	SP205907
St. Peter and Paul	Coleshill	E2	1859	SP202871
St. Saviour	Satley	E3	1849-50	SP097857
Erdington Abbey	Erdington	E4	1848-50	SP112903
St. Chad	Wishaw	E5	C13-C18	SP176925
Holy Trinity	Birchfield	E6	1864	SO067881
St. Peter and St. Paul	Aston	E7	1879-90 & 1908	SP083879
Holy Trinity	Sutton Coldfield	E8	1875-9	SP122942
St. John the Evangelist	Perry Barr	E9	1831 & 1887	SP069901
St. Mark	Great Wyrley	N1	1844-5	SJ986077
St. James	Brownhills	N2	1850-1	SK049032
St. Luke	Cannock	N3	1878-82	SJ982082
St. Giles	Willenhall	N4	1866-7	SO967965
St. Paul	Wood Green	N5	1874	SO998941
St. Peter	Harbourne	S1	1867	SP028819
St. Nicholas	Kings Norton	S2	C12-C19	SP049769
Old Church	Edgbaston	S3	1885 &1889	SP057827
St. Leonard	Frankley	S4	C12-C20	SO998784
St. Stephen	Selly Oak	S5	1870-1	SP053808
St. Mary	Selly Oak	S6	1861	SP038803
St. John Baptist	Bromsgrove	S7	C13-C19	SO956686
Holy Trinity	Old Hill	W1	1876	SO956862
St. Benedict Biscop	Wombourne	W2	1862-7	SO877912
Holy Cross	Bobbington	W3	C12-C19	SO808886
United Reformed	Tettenhall	W4	1865-9	SO876992
All Saints	Claverley	W5	C12-C20	SO793935

Table 4.1.3 Basic details of the buildings included in the survey. Year of construction refers to the whole building or if only parts of the building could be surveyed then the year refers to those parts (obtained from Pevsner (1958), Pevsner (1968), Pevsner (1974), Pevsner and Wedgwood (1966) and personal communications).

Weathering Form	Description
Relief weathering	-Less resistant parts of the sandstone weather quicker than comparatively resistant ones giving a greater relief to the stone surfaces.
Alveolar	-As above except there is no indication that a difference in durability caused the different weathering rates (also called honeycombing).
Anthropogenic	-Stonework has obviously been restored since originally built. Although this is not a form of weathering it does indicate the loss of stone by an unknown agent (possibly weathering).
Granular disintegration	-Single grains of the sandstone detach.
Spalling	-Detachment of crumbs of sandstone that are composed of several grains.
Multiple flaking	-Two or more concentric layers of stone less than 3 mm thick can be seen to be detaching.
Multiple scaling	-Two or more concentric layers of stone greater than 3 mm thick can be seen to be detaching.
Black flaking	-Detachment of a blackened surface layer where the thickness of the stone lost is less than 3 mm.
Case hardened flaking	-Detachment of a case hardened (i.e. the surface is visibly enriched by salts or re deposited cement from within the stone) surface layer where the thickness of the stone lost is less than 3 mm.
Autotrophic flaking	-Detachment of a surface layer covered with algae, moss or lichen where the thickness of the stone lost is less than 3 mm.
Unaltered flaking	-Detachment of a surface layer with no surface alteration where the thickness of the stone lost is less than 3 mm.
Black scaling	-Detachment of a blackened stone layer where the stone lost is greater than 3 mm thick.
Case hardened scaling	-Detachment of a case hardened surface layer where the thickness of the stone lost is greater than 3 mm thick.
Autotrophic scaling	-Detachment of a surface layer covered with algae, moss or lichen where the thickness of the stone lost is greater than 3 mm thick.
Unaltered scaling	-Detachment of a surface layer with no surface alteration where the thickness of the stone lost is greater than 3 mm thick.
Black soiling	-Black coating on the sandstone surface.
Case hardened soiling	-The surface is visibly enriched by salts or re-deposited cement from within the stone.
Autotrophic soiling	-The stone is covered by lichens, algae or moss.

Table 4.1.4. Classification of different sandstone weathering forms.

SHEET 1, Sandstone Building Survey, David Halsey, University of Wolverhampton			
SURVEY DATES			
BUILDING NAME			
LOCATION			
BUILDING CODE			
WALL CODE			
YEAR OF CONSTRUCTION			
CONSTRUCTION	ASHLAR / RUBBLE SMOOTH / ROUGH		
ORIENTATION (degrees E of N)			
TERRAIN ROUGHNESS	*1.0*	*0.85*	*0.75*
TOPOGRAPHY	*1.2*	*1.0*	*0.8*
GRID REFERENCE			
GEOGRAPHIC INCREMENT (i)			
ROSE VALUE (r)			
MAP VALUE (i+r)			
AIRFIELD INDICES			
DWA			
NOTES			

Figure 4.1.3. Survey Sheet 1. For categories in italics refer to definitions in Table 4.1.5.

Variable	Description
Orientation	Aspect of the wall in degrees East of North.
Grid reference	Ordnance Survey grid reference.
Geographic increment (I)	A value obtained from BS 8104:1992 which allows for the geographic location of the building.
Rose value (R)	A value obtained from BS 8104:1992 which allows for the influence of orientation upon wind driven rain.
Map value (M)	Obtained from the sum of I and R.
Airfield annual index (DA)	Obtained from BS 8104:1992 once M is known. It is the yearly sum of hourly wind speed and rainfall for a given orientation in $l\ m^{-2}\ yr^{-1}$ (based on 33 years data).
Terrain roughness (R)	An assessment of the effects of surface features upwind of the wall, upon wind speed.
Topography (T)	An assessment of the effect of local topography upon wind speed.
Obstruction (O)	An assessment of the influence of obstructions sheltering the wall.
Wall (W)	An assessment of the effects of wall design upon wind speed.
Wall annual index (DWA)	$DWA = DA \times R \times T \times O \times W$ The quantity of rain falling on the wall in the chosen location in $l\ m^{-2}\ yr^{-1}$

Table 4.1.5 Calculation of wind driven rain (after BS 8104:1992).

SHEET 2, Sandstone Building Survey, David Halsey, University of Wolverhampton						
OBSERVATION CODES						
WALL	*0.2*	*0.3*	*0.4*	*0.5*		
HEIGHT (m)	0.2-1.2					
ARCHITECTURAL UNIT	WALL / SILL					
OBSTRUCTION (m)	*0 -4 -8 - 15 - 25 - 40 - 60 - 80 - 100 - 120 >*					
WEATHERING FORM		% AFFECTED				CODE
1	RELIEF					
2	ALVEOLAR					
3	ANTHROPOGENIC					
4	GRANULAR DISINTEGRATION					
5	MULTIPLE FLAKES					
6	MULTIPLE SCALING					
7	SPALLING					
		BLACK	CASE	ORGANIC	NONE	
8	FLAKING					
9	SCALING					
10	SOILING					
HEIGHT (m)	1.2 - 2.2					
ARCHITECTURAL UNIT	*WALL / SILL*					
OBSTRUCTION (m)	*0 -4 -8 - 15 - 25 - 40 - 60 - 80 - 100 - 120 >*					
WEATHERING FORM		% AFFECTED				CODE
1	RELIEF					
2	ALVEOLAR					
3	ANTHROPOGENIC					
4	GRANULAR DISINTEGRATION					
5	MULTIPLE FLAKES					
6	MULTIPLE SCALING					
7	SPALLING					
		BLACK	CASE	ORGANIC	NONE	
8	FLAKING					
9	SCALING					
10	SOILING					

Figure 4.1.4 Survey Sheet 2.

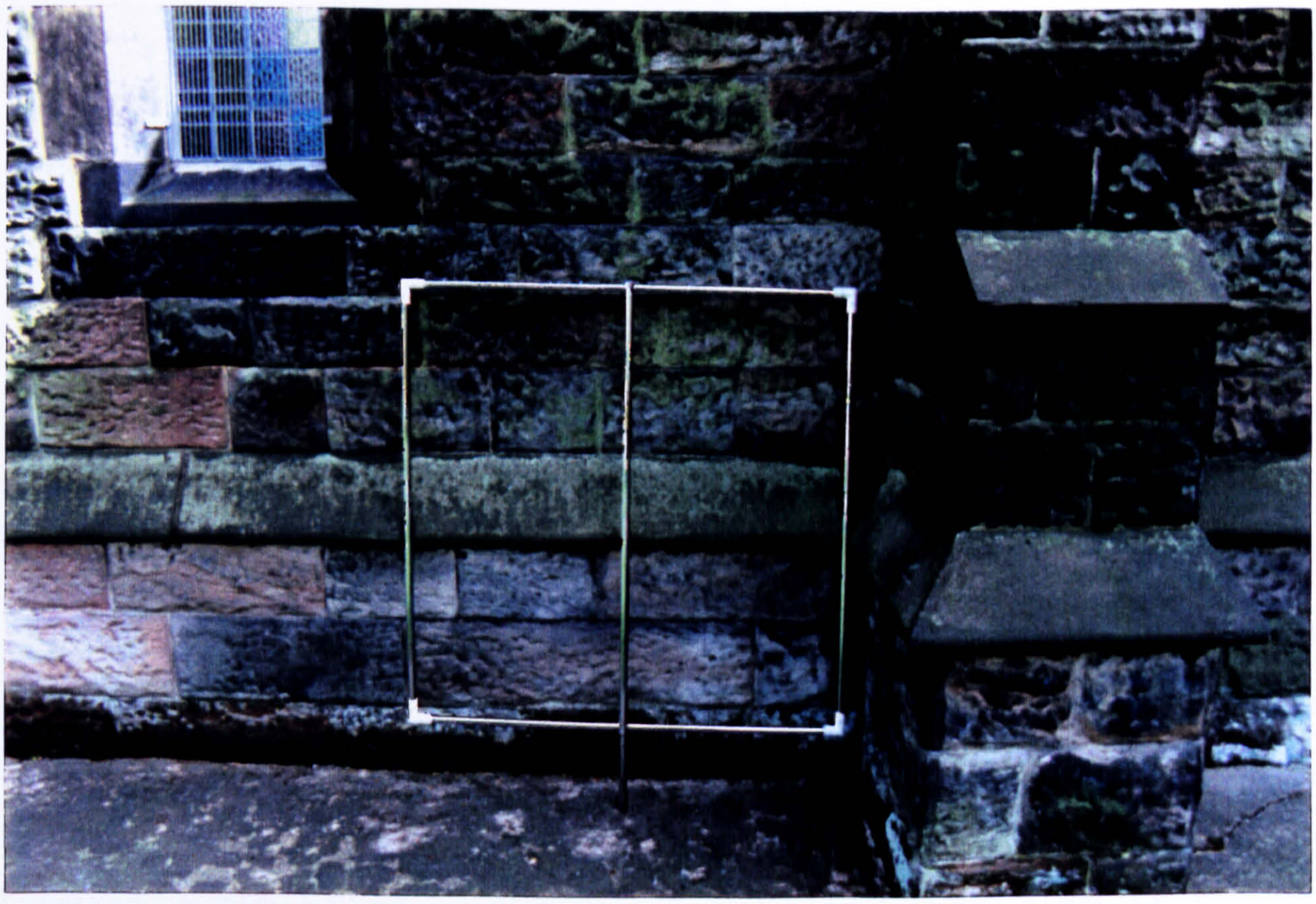

Plate 4.1.4 Surveying quadrat.

Weathering Type	Description
Total blackened stone	The sum of black flaking, black scaling and black soiling.
Total autotrophic stone	The sum of autotrophic flaking, autotrophic scaling and autotrophic soiling.
Total case hardened stone	The sum of case hardened flaking, case hardened scaling and case hardened soiling.
Total flaking	The sum of black flaking, autotrophic flaking and case hardened flaking.
Total scaling	The sum of black scaling, autotrophic scaling and case hardened scaling.
Total soiling	The sum of black soiling, autotrophic soiling and case hardened soiling.
Total	The sum of all weathering forms.

Table 4.1.6 Classification of different sandstone weathering types.

4.2 RESULTS AND DISCUSSION

4.2.1 SANDSTONE TEMPERATURES AND MOISTURE CONTENTS

4.2.1.1 Results

Mean monthly sandstone temperatures show, as expected, seasonal trends with values around 5°C in winter months (December to February) and 18°C in summer months (June to August) (Table 4.2.1 and Figure 4.2.1). Aspect exerts an influence with mean values for the south, east and west being higher than those for the north. In contrast, the minimum monthly sandstone temperatures are not influenced by aspect (Figure 4.2.1). Minimum temperatures, which are dominantly affected by air temperatures, show marked seasonal variations with temperatures as low as -4°C in winter months. Maximum monthly sandstone temperatures also show a seasonal trend, with maxima around 15°C in winter months and 35°C in summer months (Table 4.2.1). Aspect influences the maximum monthly sandstone temperatures with values being greatest for the west and south. In June 1995 a maximum temperature of 44°C was recorded for the west facade giving an annual temperature range of 48°C (Figure 4.2.1).

Mean monthly temperature changes per fifteen minutes are low, about 0.2°C, with values being slightly higher in summer months than in winter months (Table 4.2.1 and Figure 4.2.2). Aspect influences the mean rates of temperature change with the south and west and, to some extent, the east, experiencing greater rates than the north. The minimum temperature changes per fifteen minutes is 0°C in all cases as stable temperatures often exist. The most pronounced influence of aspect is on the maximum rates of temperature change with the west aspect experiencing some very rapid temperature changes, the greatest being 7°C in June 1994 (Figure 4.2.2).

The monthly frequency with which sandstone heating and cooling rates exceed 1°C in fifteen minutes (rapid heating and cooling), shows a marked seasonal trend, with rapid heating and cooling being more common in summer months than in winter months (Table 4.2.1 and Figure 4.2.3). Aspect influences rapid heating and cooling, with the north aspect experiencing very few cases of rapid heating, but an intermediate amount of rapid cooling

during summer months (Figure 4.2.3). The south aspect shows a similar pattern to that of the east, with the occurrence of rapid heating being greater than rapid cooling. However, both rapid heating and rapid cooling are greater for the south than the east aspect, especially during winter months (Figure 4.2.3). The west aspect shows a similar amount of rapid heating to the south, although the seasonal pattern of monthly values differs (Figure 4.2.3). Rapid cooling is far more common for the west aspect than any of the others and is the only aspect where rapid heating and rapid cooling have similar monthly occurrences (Figure 4.2.3).

The number of monthly heating-cooling cycles is influenced by aspect, with the south and west experiencing more cycles than the north and east aspects (Figure 4.2.4). A seasonal trend can be seen for all aspects, but it is most pronounced for the north and east. During the study period more heating-cooling cycles occurred in summer than in winter months, for all aspects (Table 4.2.1 and Figure 4.2.4).

Mean monthly sandstone relative humidity (RH) is influenced by aspect, with values typically being much lower for the south aspect (Figure 4.2.5). Seasonal variations are also apparent, with mean RH being higher in winter months than in summer months (Table 4.2.1). Maximum monthly sandstone RH shows a very similar trend, with maxima around 100% during winter months for all aspects, but lower during summer months, especially for the south aspect (Figure 4.2.5). Minimum monthly sandstone RH also follow this trend, with higher values in winter months than in summer months and noticeably lower values for the south aspect (Table 4.2.1). The typical monthly range in sandstone RH is greatest for the south and west aspects (Figure 4.2.5).

Mean rates of RH change are typically around 0.2% in fifteen minutes (Table 4.2.1). These rates do not differ greatly due to aspect, but are slightly higher in summer months than in winter months (Figure 4.2.6). Relative humidity change is typically very slow, however, some rapid changes were recorded, especially for the west orientation which experienced an RH change of 12% in fifteen minutes in June 1994 and March 1995 (Figure 4.2.6).

The monthly frequency of wetting-drying cycles is noticeably higher in summer months, than in winter months (Table 4.2.1 and Figure 4.2.7). Aspect influences the number of cycles, with the west and to a lesser extent the south aspects experiencing a greater number of cycles than the north and east.

The monthly frequency of wet-dry cycles is highest in summer with no cycles occurring for any aspect from November 1994 to February 1995 (Figure 4.2.8). The west aspect experiences the greatest number of cycles.

The Time of Wetness (TOW) demonstrates seasonal fluctuations, with values being much higher in winter months than in summer months (Table 4.2.1 and Figure 4.2.9). In fact, from November 1994 to February 1995 all orientations were constantly wet (RH>80%). As a result TOW in these months is not influenced by aspect, but for other months the TOW is lowest for the south aspect (Figure 4.2.9).

During the monitoring period the number of freeze-thaw cycles experienced by the sandstone is very low (Figure 4.2.10). Aspect has a limited influence on the number of cycles, with the total number being 39, 28, 34 and 36 for the north, east, south and west aspects, respectively.

A summary of the influence of aspect upon the temperature and moisture conditions of the stones at Lichfield Cathedral is provided in Figure 4.2.11.

	Spring				Summer				Autumn				Winter			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
Mean monthly sandstone temperature (^{o}C)	9.0	10.3	10.7	10.0	16.8	18.1	18.1	17.7	10.3	10.9	11.5	11.3	4.9	5.2	5.8	5.6
Maximum monthly sandstone temperature (^{o}C)	21.2	25.5	28.5	30.7	32.2	36.0	36.9	41.6	17.0	19.6	24.9	29.3	12.4	13.2	17.9	18.2
Minimum monthly sandstone temperature (^{o}C)	0.9	1.3	1.1	0.9	8.2	8.5	8.3	8.1	2.7	2.9	3.3	3.1	-2.4	-2.1	-2.0	-2.3
Mean monthly rate of temperature change (^{o}C)	0.2	0.3	0.3	0.4	0.3	0.3	0.4	0.4	0.1	0.1	0.2	0.3	0.1	0.1	0.2	0.2
Maximum monthly rate of temperature change (^{o}C)	2.7	3.6	4.2	5.1	2.4	3.2	3.7	4.1	2.3	2.8	4.2	5.5	2.6	1.7	3.6	4.5
Rapid heating (number month^{-1})	5.5	106.5	146.5	113.0	17.5	117.5	143.0	149.2	0.7	48.0	96.3	103.3	0.5	11.3	63.0	55.8
Rapid cooling (number month^{-1})	15.0	33.7	62.0	113.7	42.2	38.8	44.3	134.3	3.0	16.3	41.3	90.3	3.3	5.5	31.8	45.7
Heating-cooling cycles (number month^{-1})	18.8	21.0	27.0	28.7	24.7	25.5	29.2	30.2	9.3	8.0	22.3	24.3	4.7	5.3	17.2	19.2
Mean monthly relative humidity (%)	88.8	94.6	72.0	81.3	71.0	76.6	ND	69.9	96.1	93.5	83.3	92.9	99.0	96.0	96.4	98.9
Maximum monthly relative humidity (%)	100	99.3	94.0	97.0	88.2	85.7	ND	94.3	100.0	98.0	95.0	100.0	100.0	99.0	100.0	100.0
Minimum monthly relative humidity (%)	76.3	88.7	46.3	50.0	48.2	61.8	ND	35.7	87.3	79.7	63.3	72.0	96.0	92.7	85.7	86.3
Mean monthly rate of relative humidity change (%)	0.2	0.2	0.3	0.4	0.3	0.3	ND	0.4	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Maximum monthly rate of relative humidity change (%)	4.0	4.7	5.0	8.3	3.5	6.2	ND	6.8	3.3	2.7	3.0	5.0	2.0	2.3	5.3	6.7
Wetting-drying cycles (number month^{-1})	9.0	0.3	14.0	25.7	14.2	4.7	13.5	21.5	3.0	2.3	8.0	10.3	0.3	1.7	5.3	9.7
Wet-dry cycles (number month^{-1})	6.7	0.0	9.7	20.7	5	15.2	ND	11.5	1.0	0.0	6.7	5.3	0.0	0.0	0.0	0.0
Time of wetness (minutes month^{-1})	34885	44130	17475	24245	5653	18228	ND	7753	43545	33835	27540	40755	43200	43200	43200	43200
Freeze-thaw cycles (number month^{-1})	4.0	2.0	3.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	7.3	8.3	8.0

Table 4.2.1 Seasonal summary of temperature and moisture conditions at Lichfield Cathedral. Spring refers to March, April and May. Summer refers to June, July and August. Autumn refers to September, October and November. Winter refers to December, January and February. ND - insufficient data.

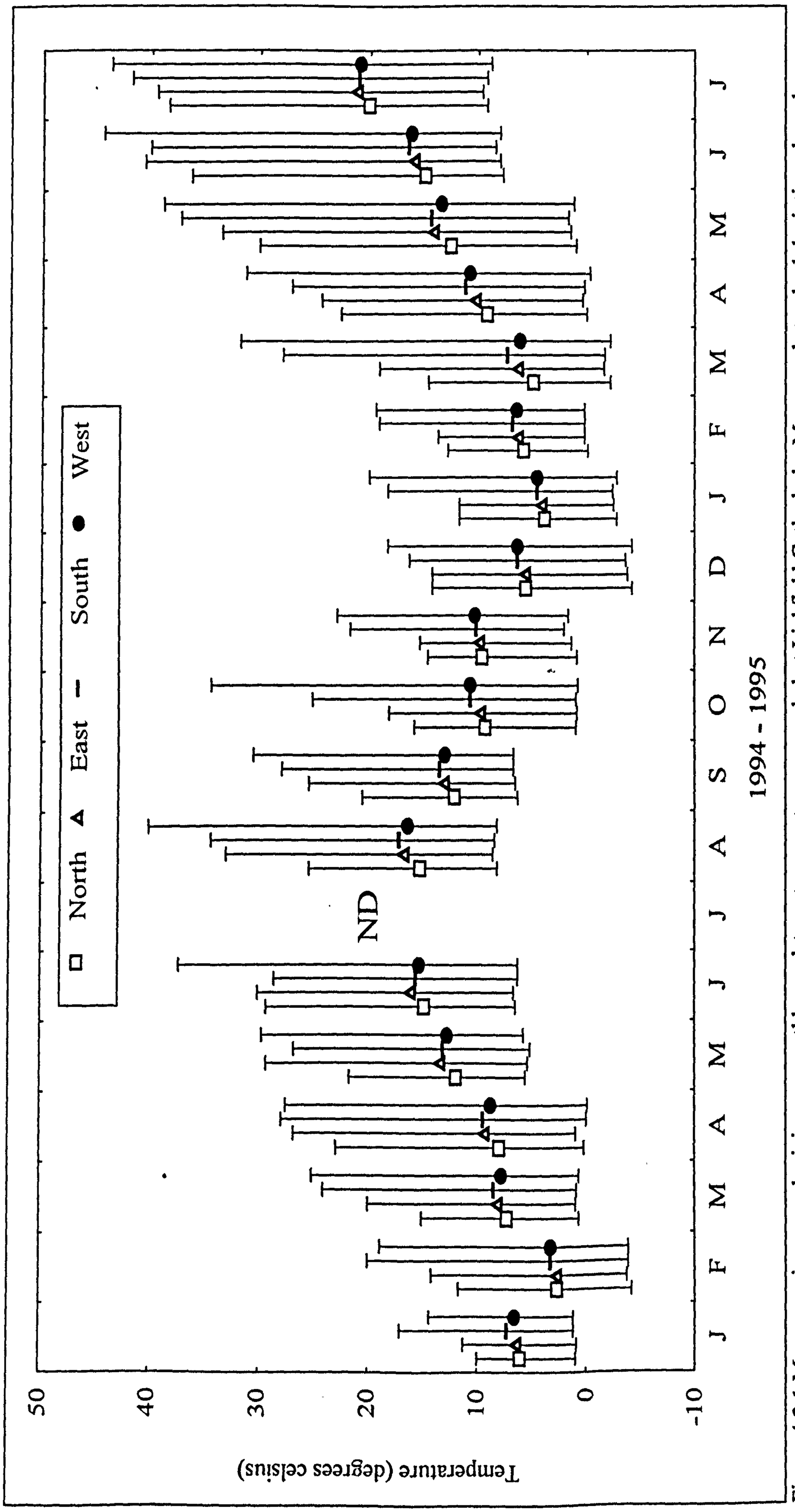

Figure 4.2.1 Mean, maximum and minimum monthly sandstone temperatures recorded at Lichfield Cathedral. Means and standard deviations have been recorded in Table A4.1.

1994 - 1995

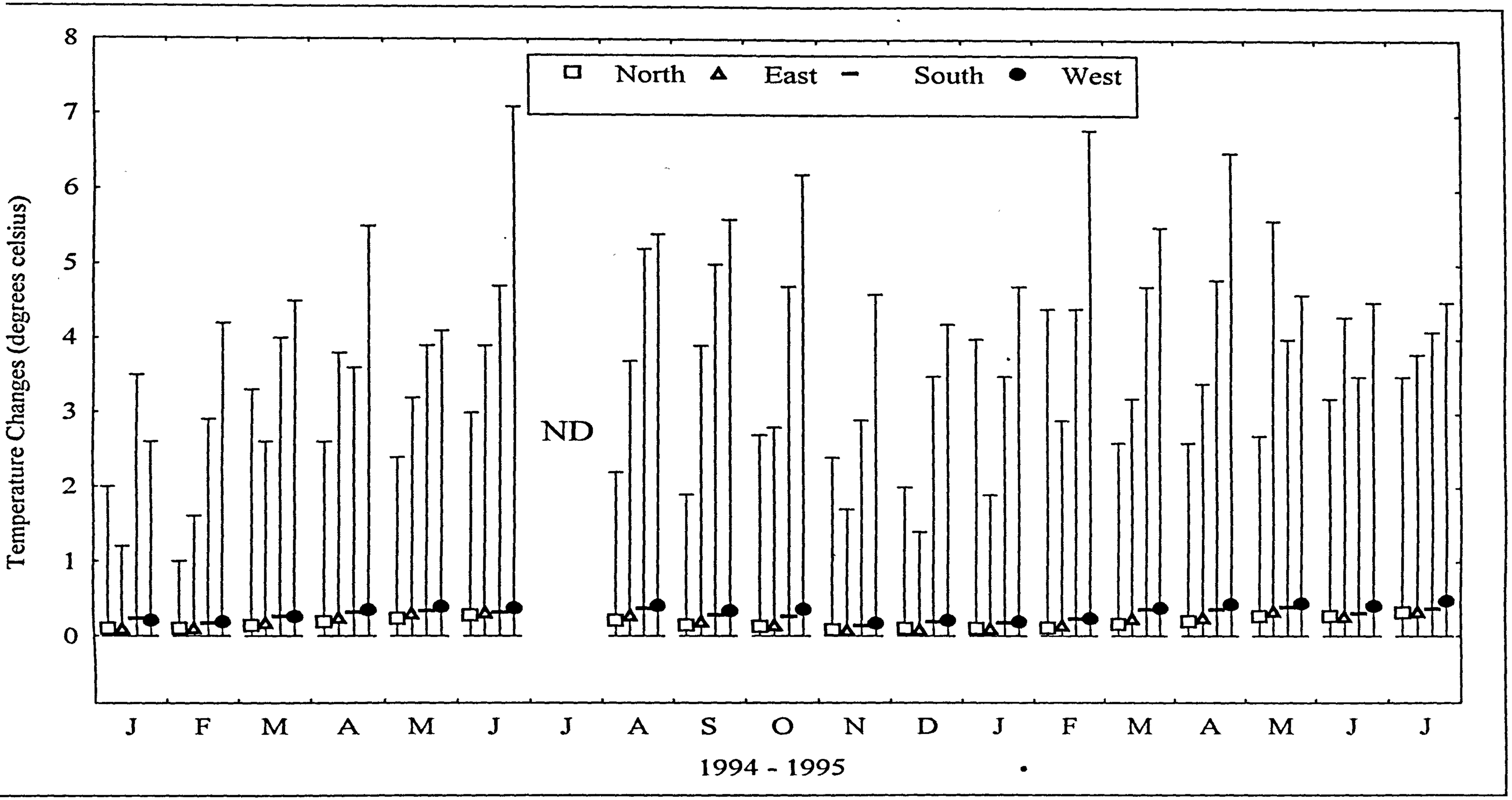

Figure 4.2.2 Mean, maximum and minimum monthly temperature changes per fifteen minutes, recorded at Lichfield Cathedral. Means and standard deviations have been recorded in Table A4.2.

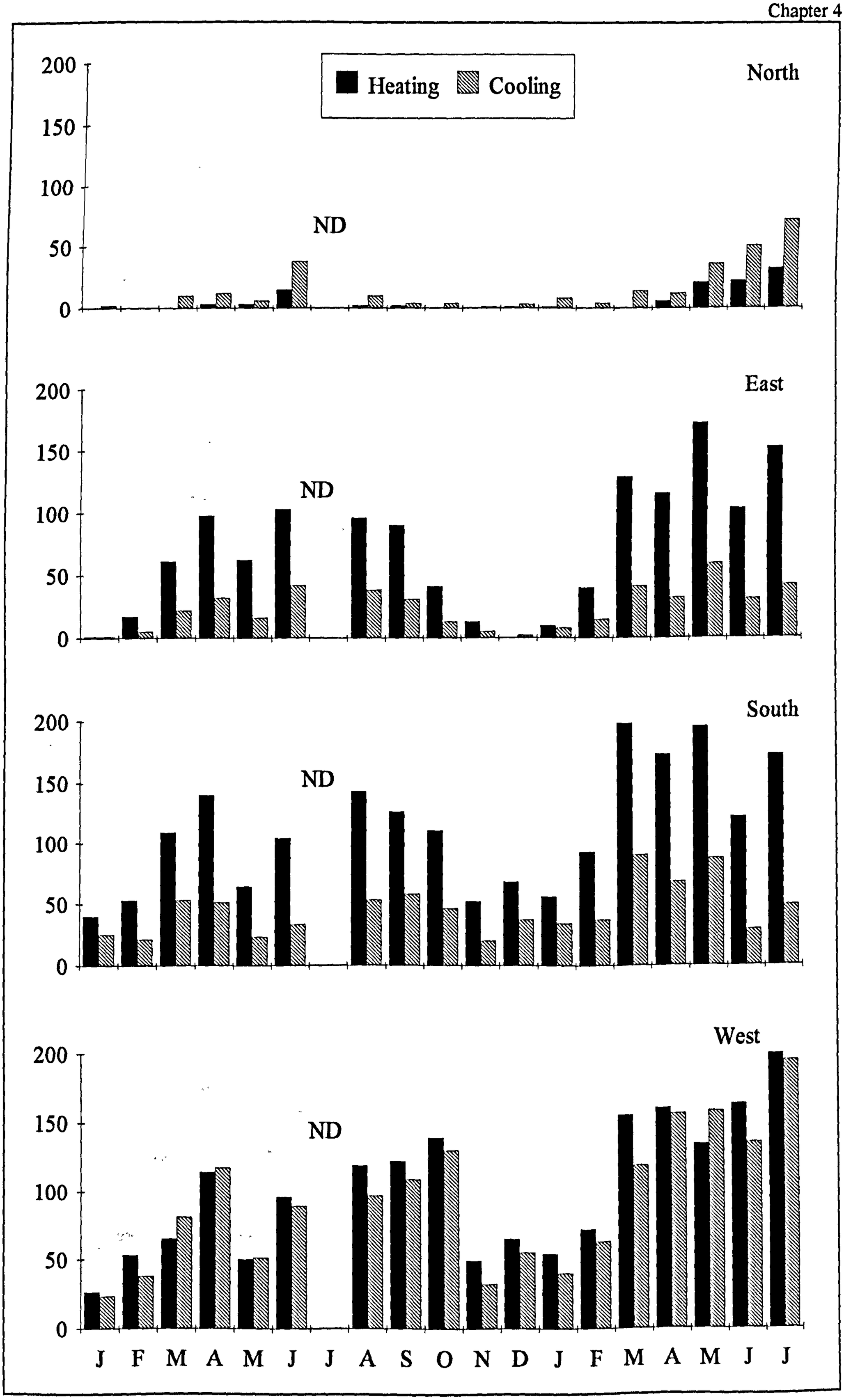

Figure 4.2.3 Number of times per month that sandstone at Lichfield Cathedral experiences rapid heating and cooling. 1994-5.

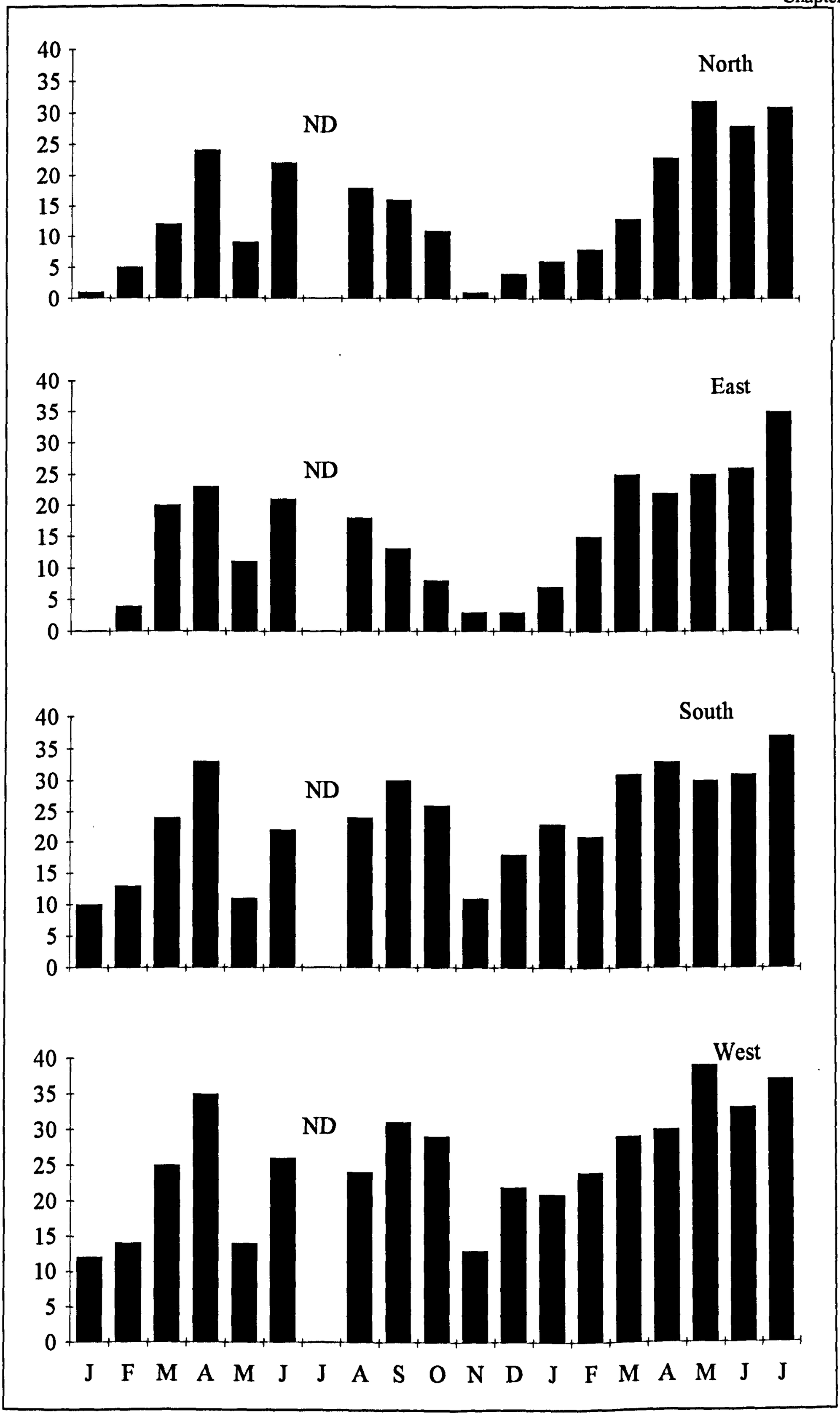

Figure 4.2.4 Number of sandstone heating-cooling cycles per month at Lichfield Cathedral.

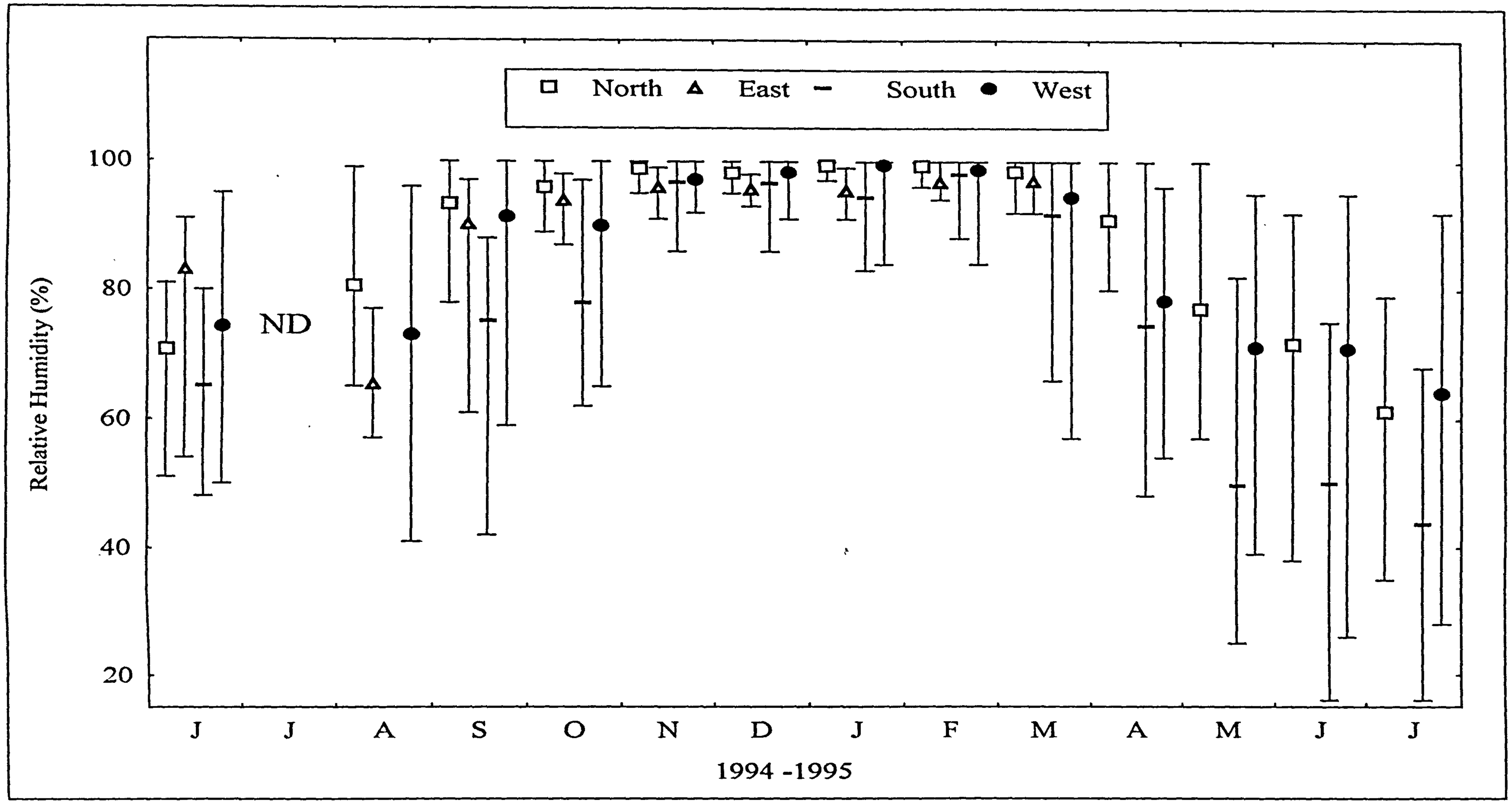

Figure 4.2.5 Mean, maximum and minimum monthly sandstone relative humidity at Lichfield Cathedral. Means and standard deviations have been recorded in Table A4.3.

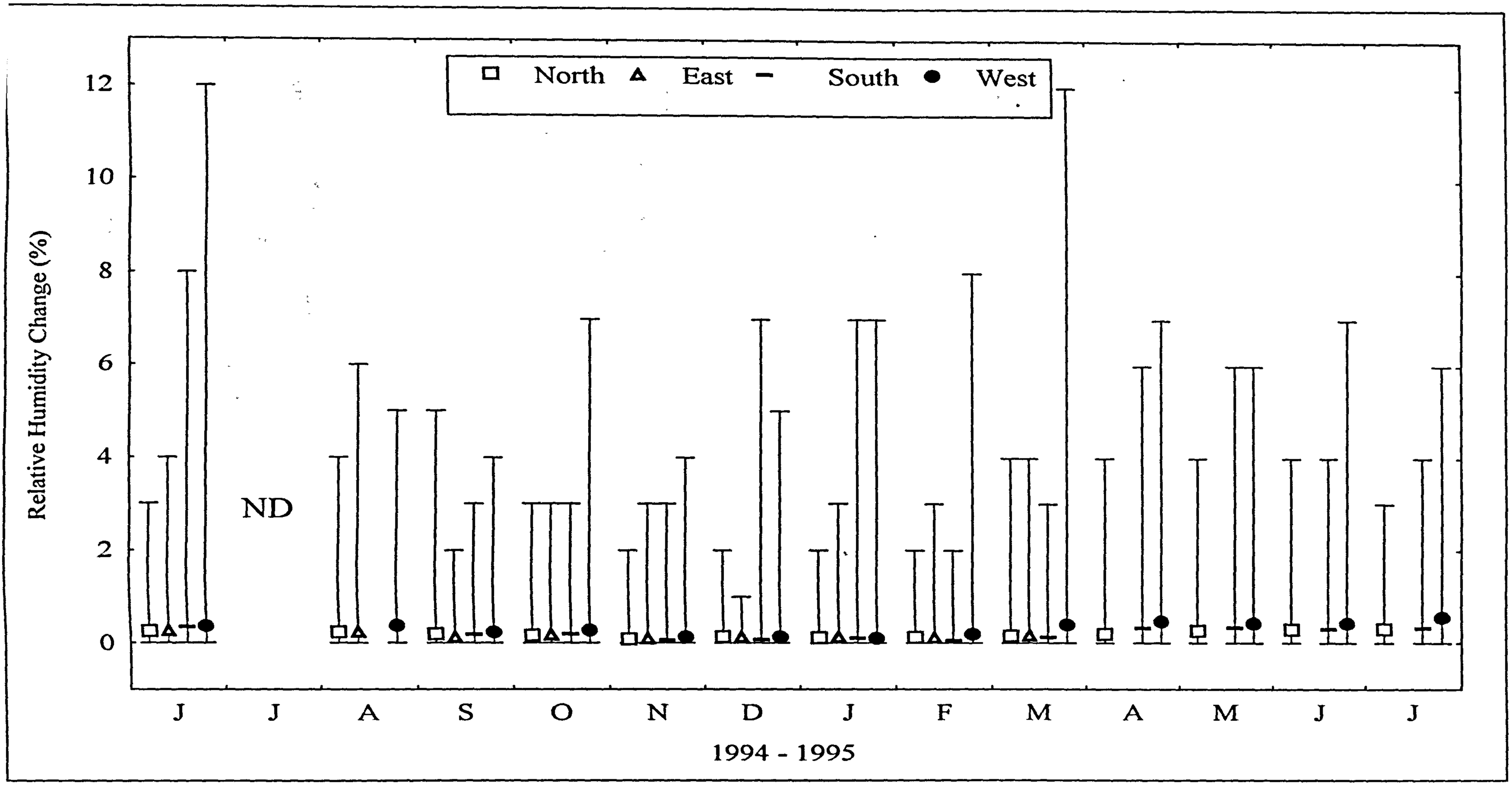

Figure 4.2.6 Mean, maximum and minimum sandstone relative humidity changes per fifteen minutes at Lichfield Cathedral. Means and standard deviations have been recorded in Table A4.4.

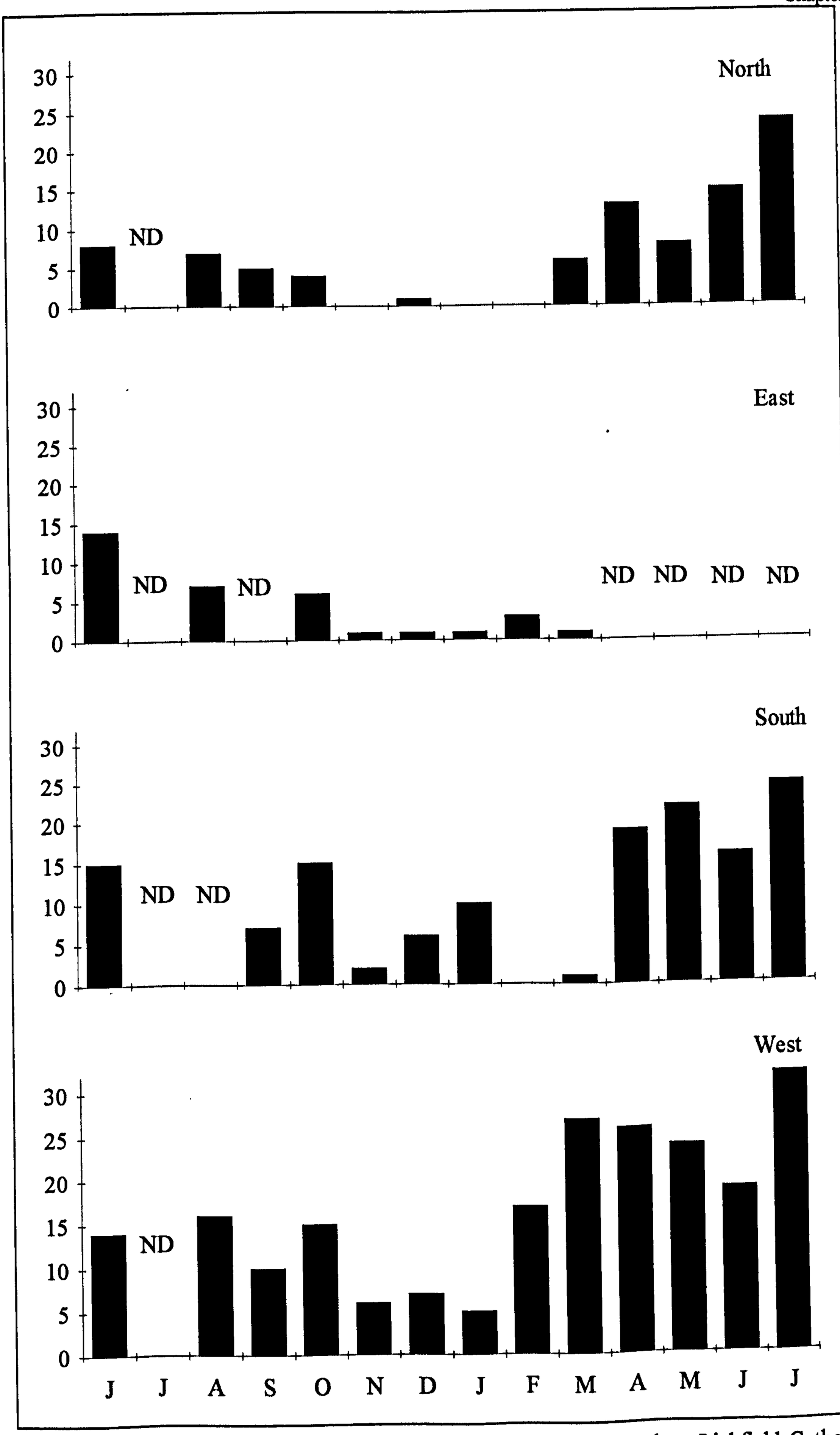

Figure 4.2.7 Number of sandstone wetting-drying cycles per month at Lichfield Cathedral. (ND - no data). 1994-5.

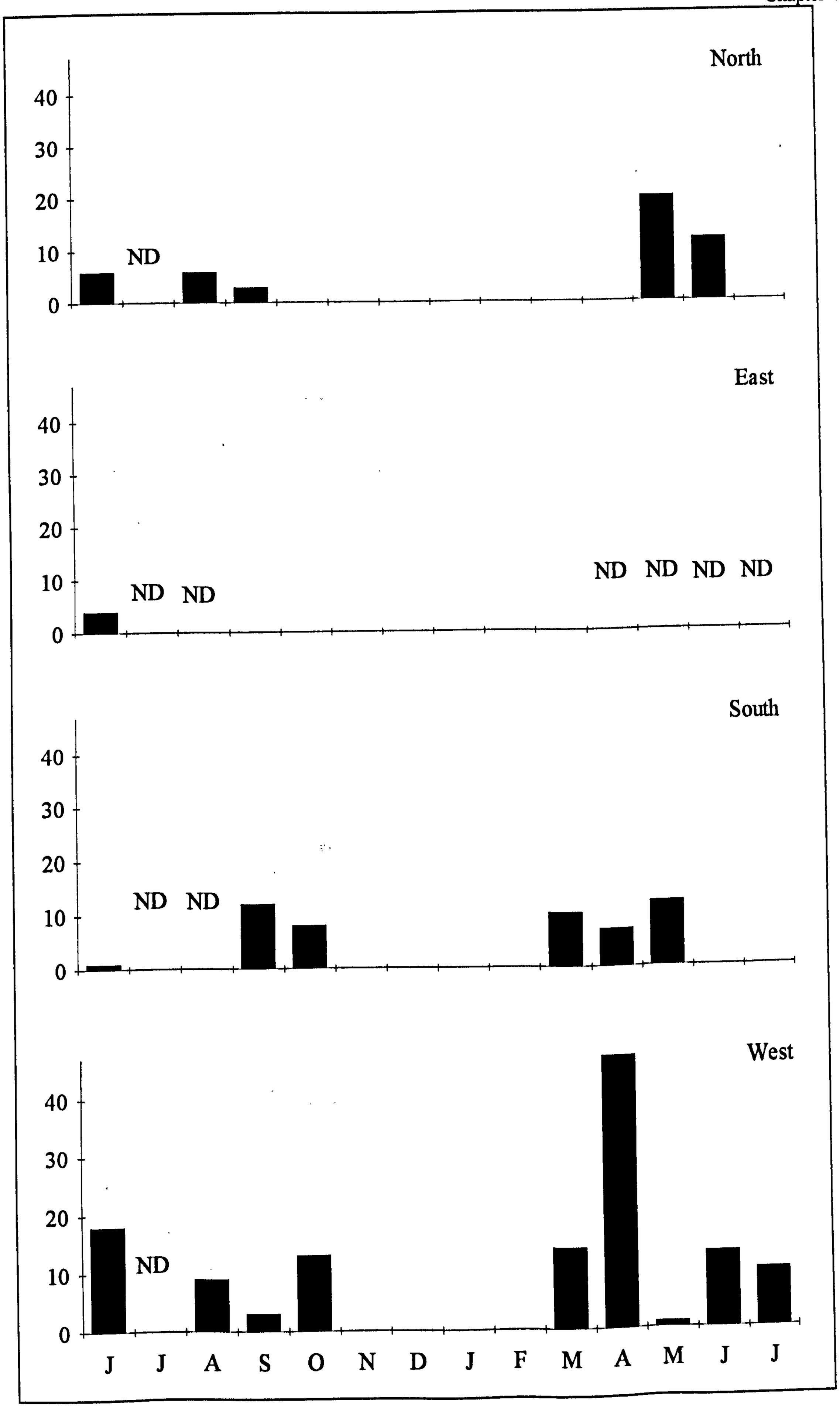

Figure 4.2.8 Number of sandstone wet-dry cycles per month at Lichfield Cathedral. 1994-5.

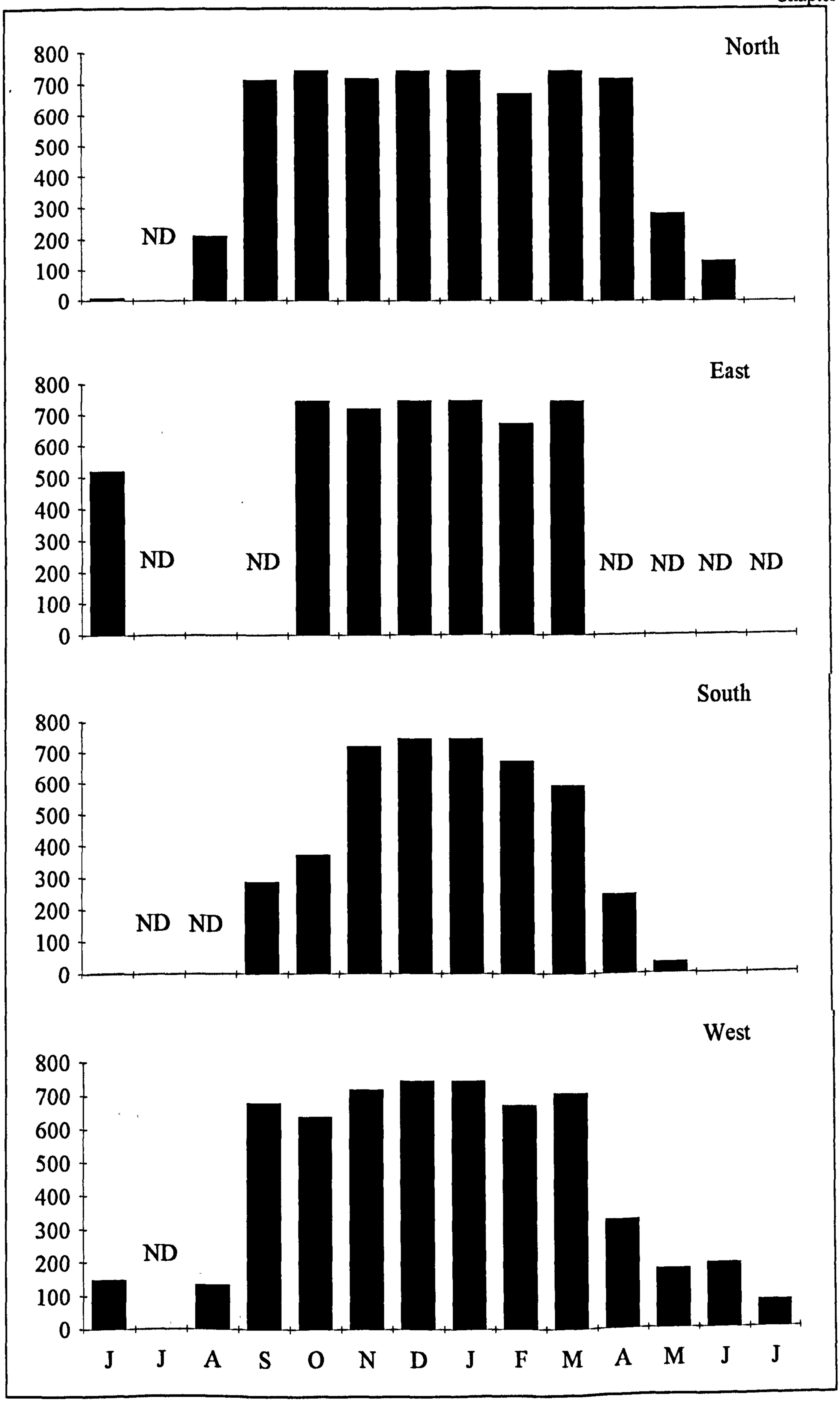

Figure 4.2.9 Sandstone Time of Wetness (hours month^{-1}) at Lichfield Cathedral. 1994-5.

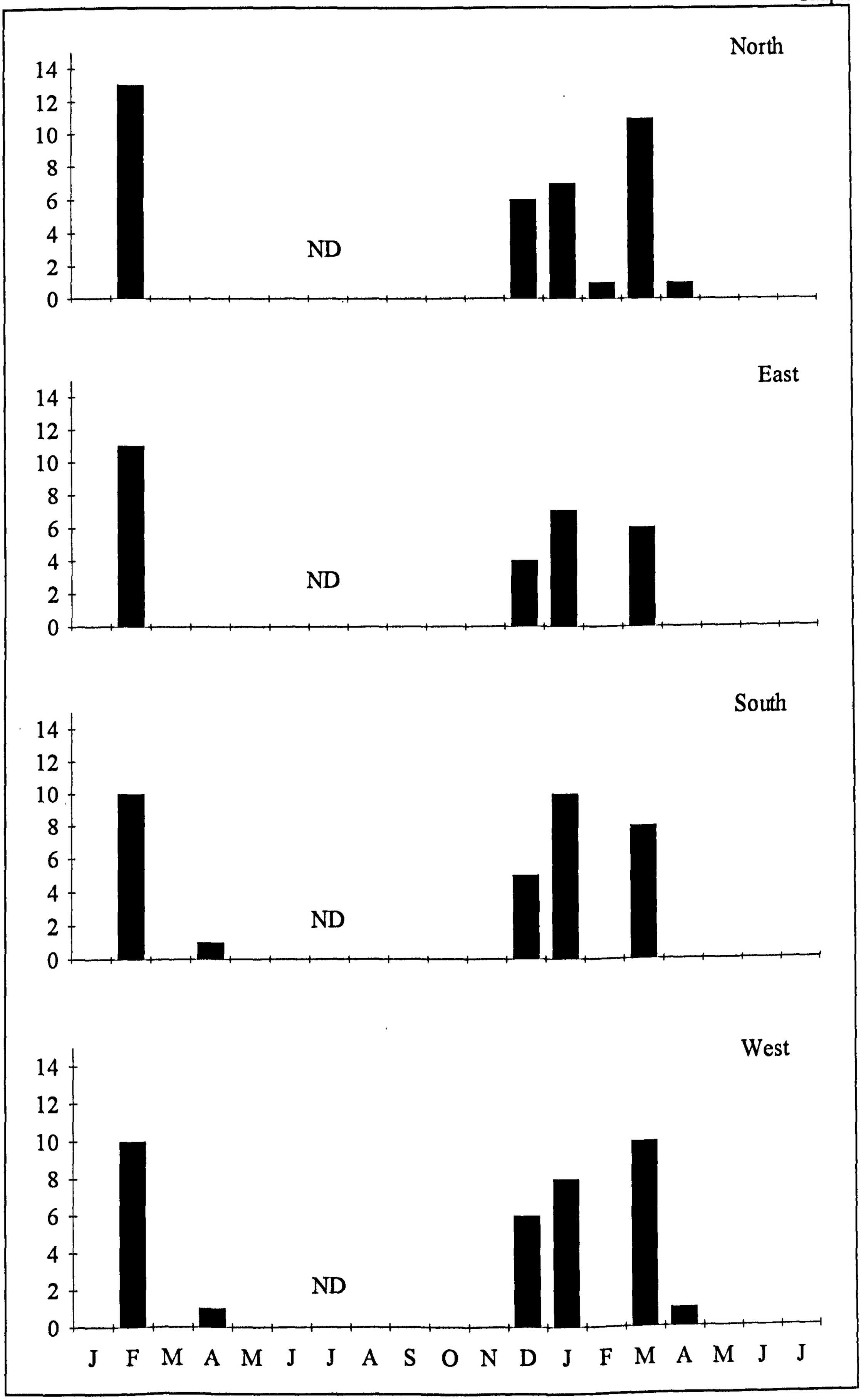

Figure 4.2.10 Number of sandstone freeze-thaw cycles per month at Lichfield Cathedral. 1994-5.

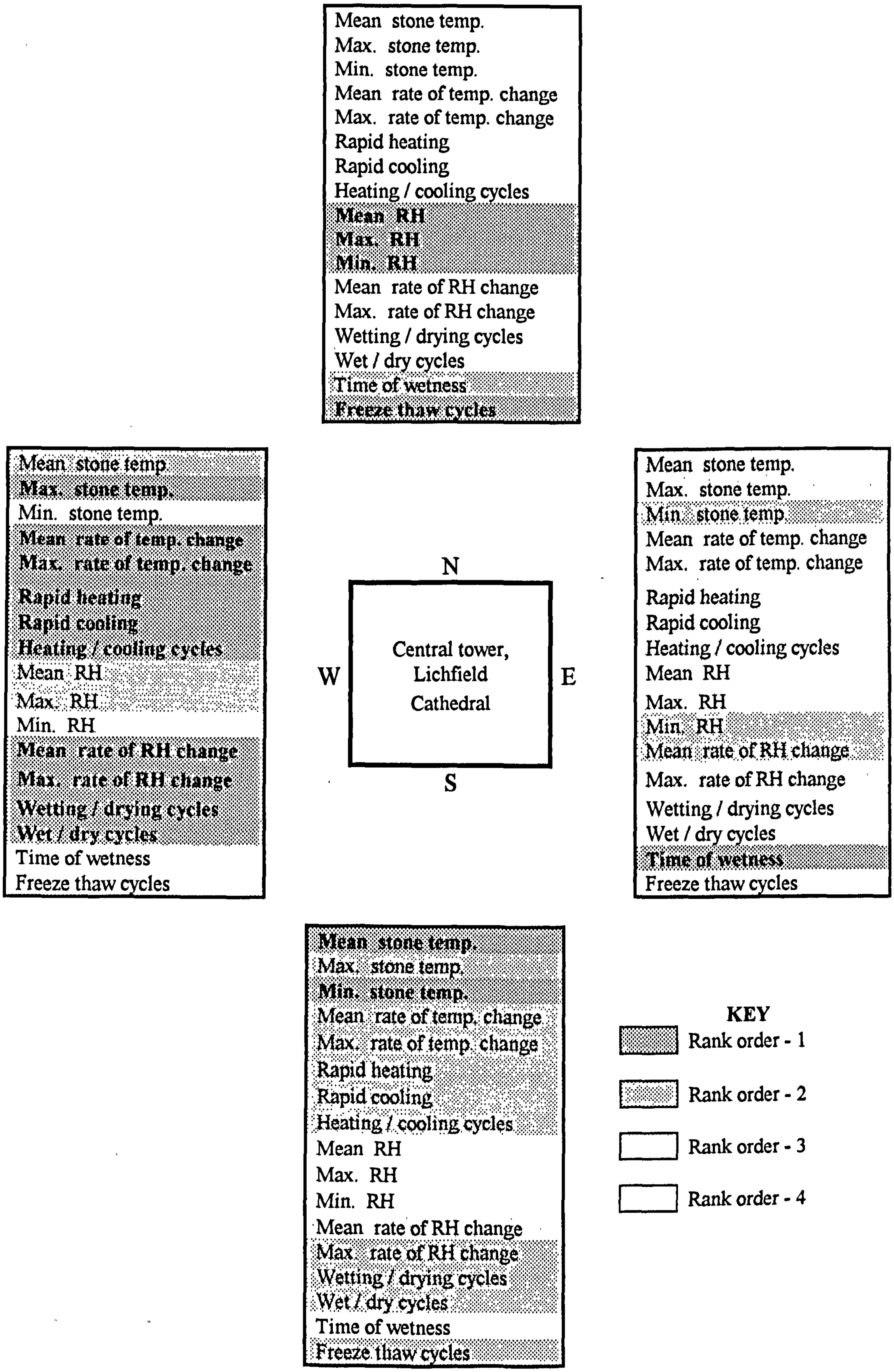

Figure 4.2.11 Rank order, descending, of measurements carried out at Lichfield Cathedral.

4.2.1.2 Discussion

Temperatures monitored at Lichfield Cathedral show that aspect exerts an influence upon the maximum sandstone temperatures (Figure 4.2.1), the rate of temperature change (Figure 4.2.2), the frequency of rapid temperature changes (Figure 4.2.3) and the number of heating-cooling cycles (Figure 4.2.4). The effects of aspect are similar for all of these measures, with the highest values being obtained for the south and west aspects, intermediate values for the east, and the lowest values for the north (Figure 4.2.11). The possible mechanisms by which temperature fluctuations may cause sandstone deterioration were reviewed in Section 1.2.1. Basically, fluctuations in temperature cause expansion and contraction movements of the sandstone. Thermal gradients cause the rates of expansion and contraction to differ with depth. Also, each mineral expands at different rates and rates of expansion differ along crystallographic axes. The stress produced by expansion and contraction is thought to be important if rapid changes in temperature occur or if repeated heating-cooling causes fatigue (Warke and Smith, 1994).

The coefficient of thermal expansion for building sandstones ranges from $7\times10^{-6}\ ^{o}C^{-1}$ to $12\times10^{-6}\ ^{o}C^{-1}$ and the modulus of elasticity from 3 to 80 kN mm^{-2} (BRE, 1979). Using these values and Equation 4.2.1, the possible range of stress imposed on the sandstone at Lichfield Cathedral can be calculated for each aspect (Table 4.2.2) .

$$\text{Stress (kN mm}^{-2}) = \text{Modulus of Elasticity (kN mm}^{-2}) \times \text{Strain}$$

where

Strain = the coefficient of thermal expansion × temperature range

Equation 4.2.1.

Sandstones used for building purposes vary greatly in compressive strength from 28 to 197 N mm^{-2} (O'Neill, 1965). The Hollington Sandstone used for the experiments in Chapter 5 has an approximate compressive strength of 32 N mm^{-2} (O'Neill, 1965). In general, the stress produced by the mean monthly sandstone temperature range is far less than the compressive strength of building sandstones (Table 4.2.2). However, it must be

recognised that tensile stresses will also be generated by contraction upon cooling. The tensile strength of sandstone is generally between 5% and 10% of the compressive strength (Young and Young, 1992). This indicates a tensile strength of between 1.6 and 3.2 N mm^{-2} for Hollington Sandstone. Therefore, if the stresses suggested by Table 4.2.2 occur in tension, failure may result. Indeed, Biggs (1994) noted the propagation of cracks in porous building materials when tensile stresses occur. It has been suggested for igneous rocks that diurnal temperature oscillations may turn a 1 μm crack into a large fracture in one year (Rosa and Silva, 1992). However, Rosa and Silva (1992) failed to define the size of a large fracture.

Fatigue effects may occur as a response to many diurnal cycles of expansion and contraction, as well as additional cycles, operating several times a day (Warke and Smith, 1994). Haimson (1974) showed that cycles of tension and compression resulted in a fatigue limit of about 30% of the compressive strength. Also, the fatigue limit is lower for wet sandstones, than for dry ones (Burdine, 1963). The number of heating-cooling cycles at Lichfield Cathedral, suggest that in summer months, diurnal cycles are very active and a small number of additional cycles may also occur for the south and west aspects (Figure 4.2.4). This observation is confirmed when examining temperature fluctuations for single days (Figure 4.2.12). Results show that on 8 June 1995 all aspects show the expected diurnal cycle, but shorter cycles underlay this main cycle, such as experienced between 16:30 and 17:45 for the west aspect (Figure 4.2.12).

The diurnal heating-cooling cycles often demonstrate rapid heating in the morning, but slow cooling at the end of the day. In contrast, the smaller heating and cooling cycles often demonstrate both rapid heating and cooling (Figure 4.2.12). Rapid temperature changes will not only increase the number of heating-cooling cycles and, therefore, the possibility of fatigue, but may also lead to deterioration by thermal shock (Warke and Smith, 1994). Temperature changes in excess of 3°C per fifteen minutes are not uncommon, especially for the south and west aspects (Figure 4.2.2). Rapid changes in sandstone temperature may occur due to the onset of rainfall or a change of wind speed (Warke and Smith, 1994). With subzero air temperatures, intermittent cloud cover, causing periods of shade, may

Aspect	Mean monthly sandstone temperature range (^{o}C)	Stress produced by mean monthly temperature range (N mm^{-2})
North	18.4	0.39 → 17.62
East	20.9	0.44 → 20.08
South	24.3	0.51 → 23.37
West	27.5	0.58 → 26.41

Table 4.2.2 Stress produced by thermal expansion due to the mean monthly sandstone temperature range for different aspects at Lichfield Cathedral.

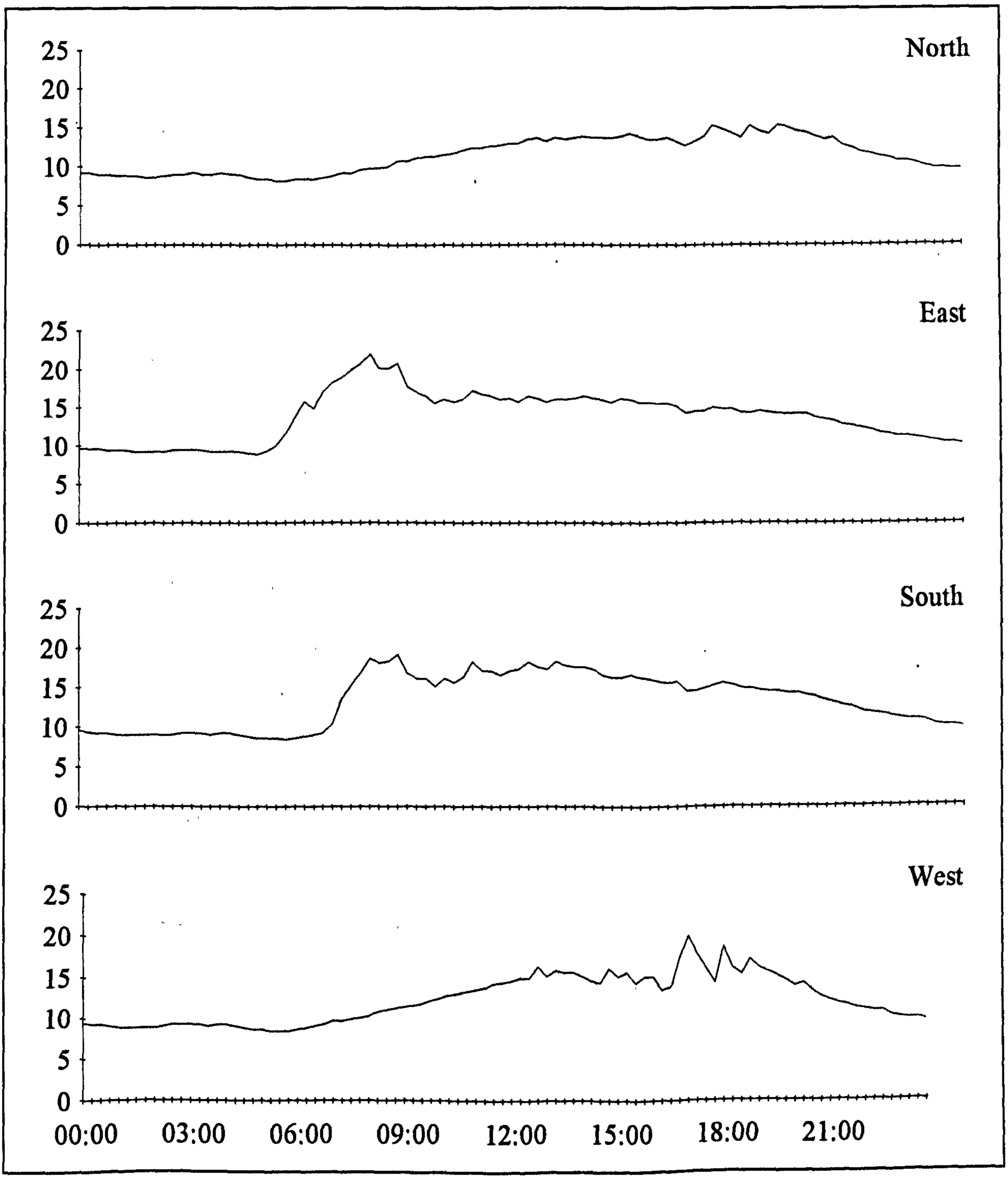

Figure 4.2.12 Sandstone temperatures recorded at fifteen minute intervals at Lichfield Cathedral on the 8 June 1995.

cause rock temperatures to fall greatly and in a simulation experiment these have been found to be in excess of 2°C min^{-1} (Hall and Hall, 1991). In the winter months of this study period, changes in temperature were lower than in the summer months (Table 4.1.2). Therefore, it seems unlikely that this mechanism was operating during the study period, as the necessary subzero daytime temperatures were uncommon, due to the generally above average air temperatures. Warke and Smith (1994) found that shading Dunhouse Sandstone from infrared lamps, which had previously heated the surface to 36.2 °C, caused a similar temperature change to that recorded at Lichfield Cathedral. However, the rate of cooling was not linear over time as the temperature dropped by 1.6 °C during the first five minutes, 1.2 °C during the second five minutes and 0.4 °C in the third five minutes. Therefore, during this study the temperature changes for fifteen minute periods may be a conservative indication of the maximum rates of change, especially over shorter time periods.

Further cycles of expansion and contraction will be caused by changes in the moisture content of the stone. The percentage movement for sandstone from a dry state to a saturated state is typically 0.07% (BRE, 1979 and Everett, 1986). However, this is only a guide and figures obtained for three sandstones in Ohio, USA, are considerably lower at 0.010%, 0.013% and 0.044% (Hockman and Kessler, 1950). The results of Hockman and Kessler (1950) for sandstone are an order of magnitude higher than the results they obtained for marble, limestone and granite, indicating that moisture cycles may be more important for sandstones than other common building stones. This may be due to the generally higher clay content of sandstones, but also the higher porosity may be important. Using the value of 0.07% for moisture expansion and the range of coefficients of thermal expansion obtained by BRE (1979), it can be calculated that the stress produced, due to a change from a dry state to a saturated one is between 2.1 N mm^{-2} and 56 N mm^{-2} (Equation 4.2.1) *. This is equivalent to the stress produced by a temperature change of between 58°C and 100°C. Therefore, these calculations show that in the worst case scenario, where a rapid change occurs from a dry state to a saturated state, far more stress may be caused to the

* Note the strain for moisture expansion is the percentage expansion divided by 100, i.e. it is the proportion of expansion per single unit rather than 100 units.

stone than by any of the recorded temperature changes. The frequency of changes from a totally dry state to a saturated state can not be calculated from the measurements taken at Lichfield Cathedral. However, sandstone RH measurements suggest that such changes will be rare, although RH changes may be reasonably rapid, as much as 6% in fifteen minutes, particularly for the south and west aspects in summer (Figure 4.2.6). These rapid changes probably occur due to drying from solar radiation and then rapid wetting due to the onset of rainfall. Schaffer (1932) points out that precipitation only causes rapid wetting of the outer layer of the stone and therefore, stress is produced between the outer layer and the core of the stone. A rapid increase in moisture content, due to rainfall, may cause the sandstone temperature to drop, causing expansion due to moisture uptake, but contraction due to a decrease in temperature. It is possible that these stresses may counteract each other, however, at the mineral scale differential expansion and contraction is likely to occur. Little information exist on the effects of moisture content upon the heating and cooling rates of sandstone, but an increased moisture content increases the thermal conductivity of the sandstone. This decreases the thermal gradient between the surface and the centre of the stone and therefore the stress between these zones will be lessened.

During the study period, the occurrence of freeze-thaw cycles is very low. Therefore, it is difficult to comment on the importance of freeze-thaw cycles at Lichfield Cathedral, due to the mild winters experienced during the study. With the exception of February 1994 all winter months (November to February) experienced higher mean daily maximum and minimum temperature than the thirty year average (Table 3.3.1).

From the above discussion it is apparent that aspects experiencing the highest rate of temperature and moisture change, and the highest frequency of temperature and moisture cycles will experience the greatest stress. South and west aspects tend to experience greater rates of temperature change (Figure 4.2.2), more heating-cooling cycles (Figure 4.2.4) and more wetting-drying cycles (Figure 4.2.7). The south aspect also tends to be the driest (Figure 4.2.5), reducing thermal conductivity, hence increasing the thermal gradient and therefore the stress. It seems reasonable that these stresses will contribute to the weathering of the stone and, therefore, a difference in weathering due to aspect can be

expected. The influence of aspect and the forms of weathering which may be caused by these stresses are considered in the next section. To evaluate this, results from the building survey are compared to those obtained from monitoring at Lichfield Cathedral. It was hoped that Lichfield Cathedral would be included in the survey, but as the cathedral was constructed and restored over many years, it was not possible to find enough comparable stones for each aspect. However, some comparable stones were found on the Central Tower of the cathedral and photographic evidence is presented which compliments the results from the building survey (Plates 4.2.1 to 4.2.4). These plates show that the north aspect experiences the most total autotrophic stone, followed by the east aspect. Some autotrophic stone is present on the west aspect, but growth is not visible on the south aspect. Total blackened stone shows the opposite trend, with the greatest occurrence on the south aspect. Relief and alveolar weathering are also visible, which are more prevalent on the south and west aspects than the north and east aspects. Photographic evidence such as this gives a subjective evaluation of the influence of aspect upon sandstone weathering. However, a quantitative evaluation of the influence of aspect upon the distribution of sandstone weathering forms is given in the following section.

4.2.2 THE INFLUENCE OF ASPECT UPON THE DISTRIBUTION OF SANDSTONE WEATHERING FORMS

4.2.2.1 Results

Results from the building survey show that total blackened stone occurs in greatest quantities on the south and west aspects, and black soiling is by far the most abundant form of total blackened stone (Figures 4.2.13 and 4.2.14). Total autotrophic stone is greatest on the north and to some extent the east aspects, with autotrophic soiling being the most important form of total autotrophic stone (Figures 4.2.13 and 4.2.14). Total case hardened stone is much less abundant than total blackened and autotrophic stone, however, it is influenced by aspect in a similar way to total autotrophic stone, with the percentage cover being highest for the north and to some extent the east aspects (Figures 4.2.13 and 4.2.14). Case hardened flaking is the most abundant form of total case hardened stone for all aspects (Figure 4.2.14).

The percentage of stone covered with relief weathering is influenced by aspect, with the south and, to a lesser degree, the west having higher cover than the east and north aspects (Figure 4.2.15). Granular disintegration, spalling and multiple flaking/scaling are also influenced by aspect, with cover being highest for the north aspect (Figure 4.2.15). Unaltered flaking covers a very small percentage of sandstone, but cover is influenced by aspect, with the lowest values occurring on the south face (Figure 4.2.15). Unaltered scaling is more common than unaltered flaking. Aspect has the opposite influence on unaltered scaling, with the highest cover being recorded for the west and south aspects (Figure 4.2.15). Alveolar and anthropogenic were recorded in the survey, but occurred in very low quantities, showing no influence from aspect.

4.2.2.2 Discussion

Using detailed microclimatic data from Lichfield Cathedral, results may indicate possible causes of the effects of aspect upon the distribution of weathering forms found by the building survey. As data from the cathedral have only been collected for a relatively short period of time and from one location, a number of assumption have to be made. Firstly, the climatic conditions experienced over eighteen months were representative of the climate experienced during the life of the buildings. This assumption is difficult to test, but Section 3.4 does show that the study period was warmer than the thirty year average, with wetter than average winters, and drier than average summers. However, over the study period maximum daily temperatures, minimum daily temperatures, total sunshine and total rainfall were above the thirty year average by 0.8^{o}C, 0.7^{o}C, 20% and 7%, respectively. Therefore, the conditions during the monitoring period were not extreme compared to the thirty year average. The second assumption is that conditions at Lichfield Cathedral were representative of the conditions experienced by the surveyed buildings. The monitoring at Lichfield Cathedral was conducted 37 m above ground level. This was selected so that local shelter would not influence the results and therefore the effects of aspect could be measured. The buildings used in the survey were affected by local shelter, as the survey was conducted between 0.2 and 2.2 m above ground level. However, thirty buildings were examined, with the aim of equalising random variations in shelter between different aspects, thereby, allowing the influence of aspect to be evaluated.

As only four aspects have been studied, at Lichfield Cathedral and in the survey, the two data sets will be analysed using the non parametric Spearman rank-correlation coefficient (r_s) (Appendix 1).

The first phase in this procedure is to simplify the data by correlating the ranks of the different measurements taken at Lichfield Cathedral against each other. This simplifies the fourteen measures into seven variables, each with a different rank order (Table 4.2.3). The same procedure is carried out for the nineteen weathering forms to produce eight groups of weathering forms, each with different rank orders (Table 4.2.4). To highlight any relationships between the measurements from Lichfield Cathedral and the survey results, the seven variables are correlated against the eight groups of weathering forms (Table 4.2.5).

The rank-correlation coefficients (r_s) between different groups of weathering forms and measurements from Lichfield Cathedral, provides a means of evaluating the importance of temperature and moisture conditions in the formation of different weathering forms. Weathering group 1 (includes granular disintegration, spalling, autotrophic scaling, autotrophic soiling and total autotrophic stone) shows a perfect positive r_s with RH, indicating that as mean monthly sandstone RH increases so does the percentage cover of the weathering forms in this group. It also shows a perfect negative r_s with temperature, indicating that higher mean monthly sandstone temperatures reduce the percentage cover of these weathering forms. This is suggesting that high moisture and low temperatures, which reduce drying, support these weathering forms. Further evidence comes from the high negative r_s with the correlated measurements* and the high positive r_s with TOW, both indicating that stable temperature and moisture conditions increase the occurrence of these weathering forms. For autotrophic scaling, autotrophic soiling and total autotrophic stone this is expected, as autotrophic activity requires a regular supply of moisture (Caneva *et al.*, 1992). For granular disintegration and spalling the explanation is not so straight forward and indeed Jenkins and Smith (1990) commented that differential thermal expansion may be

* Correlated measurements refer to the eight measurements taken at Lichfield Cathedral that have the same r_s, as shown in Table 4.2.3.

a cause of granular disintegration. However, the negative correlations with the correlated measurements suggest that expansion and contraction cycles are unimportant for granular disintegration and spalling, but relatively stable temperatures and moisture conditions may be important. Martin-Patino *et al.* (1992) noted that stones which are permanently damp, due to capillary rise, experience severe granular disintegration. For stones, such as those with a north aspect, experiencing slow evaporation, drying occurs at the surface of the stone, as opposed to at depth (Llopis *et al.*, 1992). This causes salt crystallisation to occur at the surface of the stone. Smith *et al.* (1982) considers that salt crystallisation at the surface can cause granular disintegration. Therefore, the results suggest that this mechanism is operating on parts of sandstone buildings that experience slow evaporation and may account for the higher amount of granular disintegration and spalling found on north facing walls. Although previous research gives little attention to the cause of spalling, the results suggest that the factors responsible for spalling are similar to those for granular disintegration. This seems reasonable as spalls are simply a number of grains cemented together. The reason for spalling to develop, instead of granular disintegration, is not clear, but it may be due to a higher degree of cementation or a slightly greater depth of salt crystallisation. Therefore, partial cementation of grains at the surface may remain and spalls detach as opposed to grains.

Weathering group 2 (autotrophic flaking, case hardened flaking, case hardened soiling and total case hardened stone) shows a perfect negative r_s with the correlated measurements, indicating that percentage cover of these weathering forms decreases with more variable temperature and moisture conditions. The high positive r_s with RH and the high negative r_s with temperature, RH change and wet-dry, indicate that low temperatures and regular moisture support these weathering forms in a similar way to those in weathering group 1. Therefore, it is not surprising to see autotrophic flaking in this weathering group. Case hardening occurs when soluble components of the stone are dissolved by pore water and deposited on the surface of the stone to form a hard, cemented layer (Section 2.2). For this to occur, water must have enough time to percolate through the stone, dissolving material and then evaporating at the surface of the stone. Therefore, case hardening is supported by high, stable moisture contents and low, stable temperatures, as indicated by the r_s. These

conditions allow high moisture retention times and ensure slow drying at the surface of the stone in the same way as for granular disintegration and spalling. Furthermore, the rank order of frequency for each aspect, suggest that the amount of case hardening increases for aspects with lower inputs of wind-driven rain (Figure 4.2.16) and therefore, runoff is uncommon, so the case hardening is rarely washed away. Also, water drawn up from the ground is more important as a water source for these walls than on the south and west. This water may contain dissolved salts* and passes slowly through the interior of the stone, dissolving soluble material. The dissolution of silica may be aided by the salinity of this water. This may result in a relatively saturated solution, which dries slowly at the surface of the stone giving a well cemented surface layer, with its case hardened appearance. The results show that case hardening occurs on stones that receive similar conditions to those, which experience granular disintegration and spalling. The results are inconclusive in determining which factors cause these different weathering forms to develop under similar conditions. However, it may be that case hardening occurs in preference to granular disintegration and spalling, if the capillary rise of ground water is greater and the concentration of salt in that water is greater. The salt may act as a cementing component of the case hardening, but it also affects the solubility of silica. Furthermore, case hardening may be more extensive if the stone contains considerable soluble components.

Weathering group 3 (unaltered scaling, black flaking, black scaling and total blackened stone) shows a perfect positive r_S with the correlated measurements, strong positive r_S with temperature, RH change, wet-dry, and a strong negative r_S with RH. This indicates that temperature and moisture cycles, and rapid changes in temperature and moisture may increase the cover of unaltered scaling, black flaking, black scaling and total blackened stone. Unaltered scales occur mostly on the west and south aspects. These aspects receive both solar radiation and rain, so experience rapid wetting and drying. Therefore, insolation weathering and moisture cycles may encourage scaling and flaking by the mechanisms discussed in Section 1.2. Also, evaporation is more likely to occur in the subsurface of the stone due to the higher stone temperatures experienced by these aspects. Smith *et al.* (1982) considers that salt crystallisation at depth is instrumental in causing scaling of the

* Many different salts have been reported in weathered stone. However, X-ray Diffraction, using a Phillips APD1700 Automated Powder Diffractometer, confirmed that gypsum was the predominate salt contained in weathered sandstone collected from buildings in the study area.

Plate 4.2.1 North aspect of the Central Tower, Lichfield Cathedral.

Plate 4.2.2 East aspect of the Central Tower, Lichfield Cathedral.

Plate 4.2.3 South aspect of the Central Tower, Lichfield Cathedral.

Plate 4.2.4 West aspect of the Central Tower, Lichfield Cathedral.

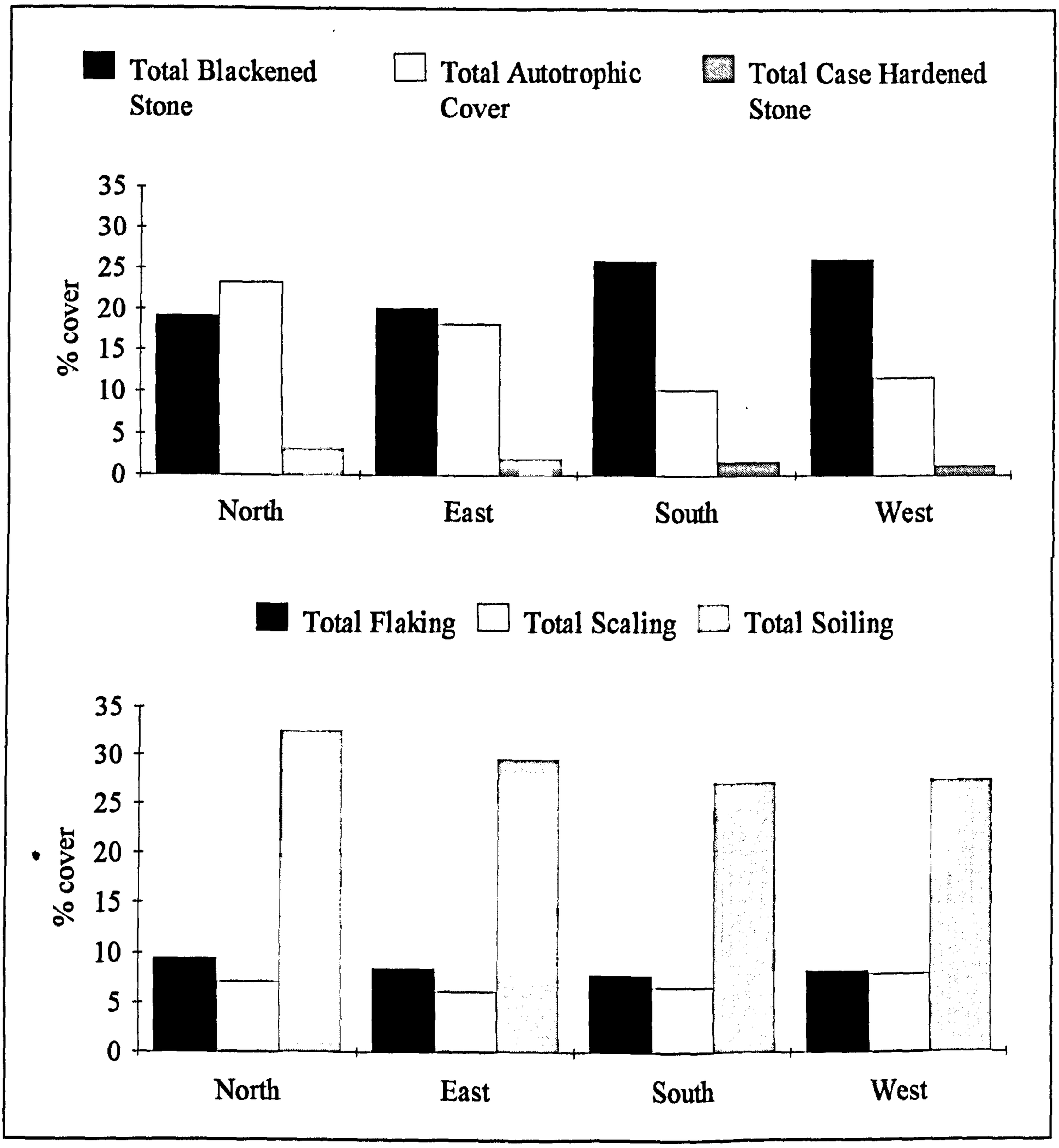

Figure 4.2.13 The effects of orientation upon the occurrence of blackened stone, autotrophic stone, case hardened stone, total flaking, total scaling and total soiled.

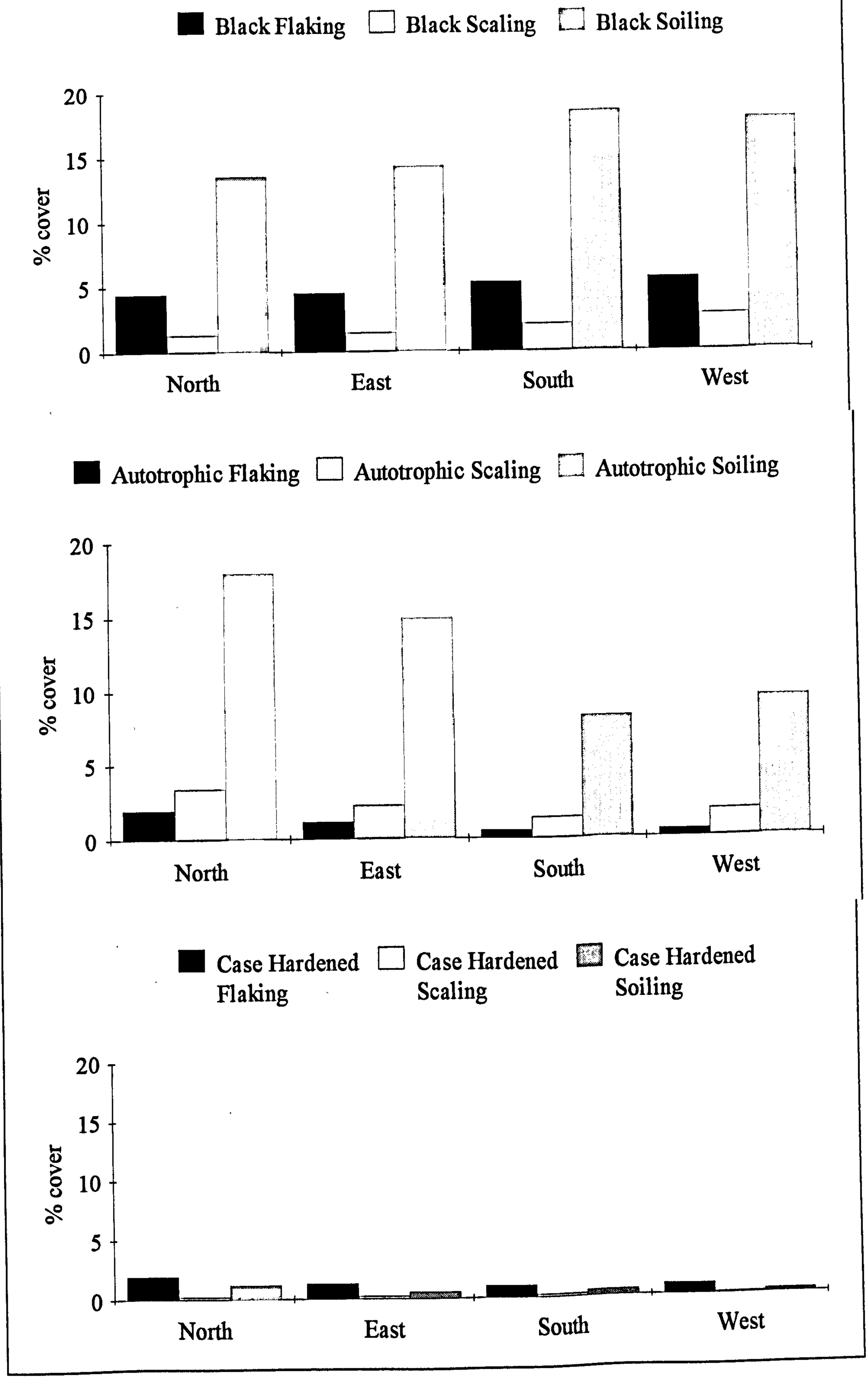

Figure 4.2.14 The effects of orientation upon the occurrence of different types of flaking, scaling and soiling.

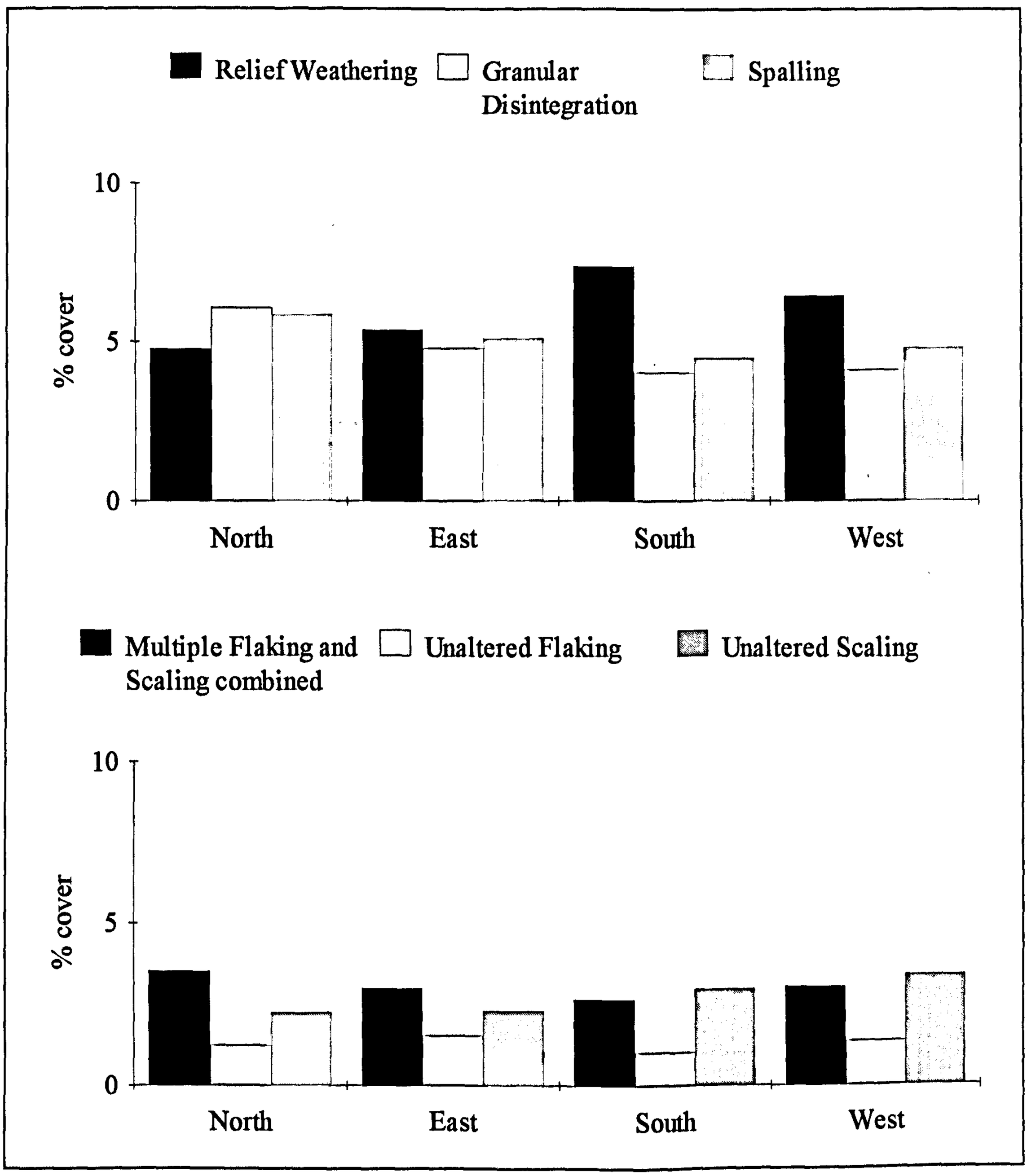

Figure 4.2.15 The effects of orientation upon the occurrence of multiple flaking, unaltered flaking, unaltered scaling, relief weathering, granular disintegration and spalling.

Rank order (descending)	Measurements with the rank order
W S E N	Temp. range, temp. change, max. temp. change, rapid heating, number of heating-cooling cycles, RH range, max. RH change and number of wetting-drying cycles ✙.
S W E N	Temperature.
W E S N	RH change.
W S N E	Number of wet-dry cycles.
N S W E	Number of freeze-thaw cycles.
E N W S	Time of wetness.
N E W S	RH.

Table 4.2.3 Grouping of mean monthly measures using their ranks. ✙ Eight of the measures are correlated into one group, which will be referred to as correlated measures in the text..

Rank Order (descending)	Weathering forms with the rank order	Weathering group
N E W S	Granular disintegration, spalling, autotrophic scaling, autotrophic soiling and total autotrophic stone.	1
N E S W	Case hardened flaking, autotrophic flaking, case hardened soiling and total case hardened stone.	2
W S E N	Black flaking, black scaling, unaltered scaling and total blackened stone.	3
S W E N	Relief weathering and black soiling.	4
N W E S	Multiple flaking/scaling combined.	5
E W N S	Unaltered flaking.	6
E S W N	Alveolar.	7
S W N E	Case hardened scaling.	8

Table 4.2.4 Grouping of weathering forms into weathering groups using their ranks.

Variable	Weathering group							
	1	2	3	4	5	6	7	8
Correlated	-0.8	**-1.0**	**1.0**	0.8	-0.4	0.0	0.2	0.6
Temperature	**-1.0**	-0.8	0.8	**1.0**	-0.8	-0.4	0.4	0.8
RH change	-0.4	-0.8	0.8	0.4	-0.2	0.6	0.4	0.0
Wet-dry	-0.6	-0.8	0.8	0.6	0.0	-0.4	-0.4	0.8
Freeze-thaw	0.2	0.4	-0.4	-0.2	0.4	-0.8	-0.8	0.4
TOW	0.8	0.6	-0.6	-0.8	0.4	0.8	0.2	**-1.0**
RH	**1.0**	0.8	-0.8	**-1.0**	0.8	0.4	-0.4	-0.8

Table 4.2.5 Spearman rank-correlation coefficients (r_s) between variables and weathering groups. Bold numbers represent a perfect positive or negative correlation.

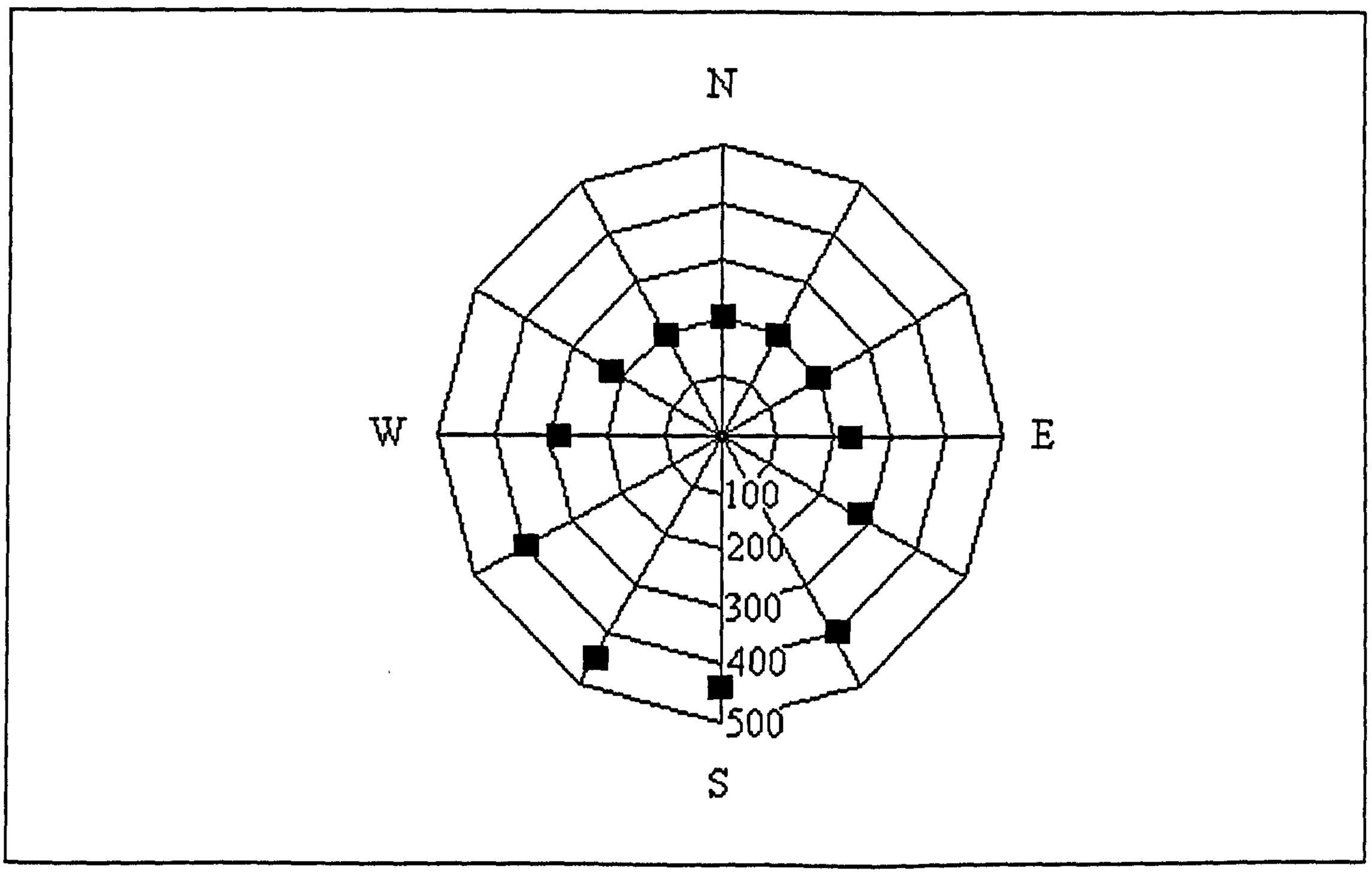

Figure 4.2.16 Average quantity (l m^{-2} yr^{-1}) of driving rain 10m above ground level in the middle of an open space in Birmingham (calculated from BS 8104:1992).

stone. Presumably, the depth of crystallisation determines whether flaking or scaling is experienced.

Weathering group 4 (relief weathering and black soiling) shows a perfect positive r_s with temperature and consequently a perfect negative r_s with RH. The strong positive r_s with the measured variables and the strong negative r_s with TOW suggest that higher temperatures, lower moisture contents, and reasonably rapid changes in moisture content and temperature, increase the cover of relief weathering and black soiling. The preference of black weathering forms for south and west aspects may be related to the fact that these facades are exposed to the prevailing winds. The increased inputs of wind-driven rain, experienced by these aspects (Figure 4.2.16), increases wet deposition and possibly the adhesion of particulate matter. The influence of the prevailing wind on dry deposition is inconclusive. As discussed in Section 2.3, dry deposition of atmospheric particles may operate by several mechanisms, which are dependant on particle size (Table 2.3.1). Inertial impact of particles onto the south and west aspects may be increased by the prevailing wind, under light wind conditions. However, the inverse is true for strong wind conditions (Verhoef, 1988). Unfortunately Verhoef (1988) fails to indicate the wind speeds for strong and light winds. The finding that blackened stone is more prevalent on south and west aspects than north and east aspects, suggests that dry deposition by thermophoresis and Stefan flow (Table 2.3.1) are not dominant deposition mechanisms, causing blackening. If they were, blackening would be more intense on the north aspect, as the lower temperature of this aspect supports deposition by thermophoresis and encourage condensation, which causes deposition by Stefan flow.

Weathering group 5 (multiple flaking/scaling combined) does not show a perfect r_s with any variable, however there is a strong negative r_s with temperature and a strong positive r_s with RH, indicating that low temperatures and high moisture contents increase cover.

Weathering groups 6 (unaltered flaking) and 7 (alveolar) also fail to show a perfect r_s, however, there is a strong positive r_s for unaltered flaking with TOW, and a strong negative r_s for unaltered flaking and alveolar with freeze-thaw. Unaltered flaking is most common

on east and west aspects. The reason for this is somewhat unclear, but it may be caused by rapid heating, due to solar radiation. The fact that alveolar is more common on the east aspect than the west and south aspects, support the claim made by Young and Young (1992), that alveolar are not the result of aeolian abrasion. If aeolian abrasion was important, the south and west aspects would be expected to have the highest occurrence. Although the results provide more evidence against aeolian abrasion, they fail to provide further evidence on the actual mechanisms causing alveolar.

Weathering group 8 (case hardened scaling) shows a perfect negative r_s with TOW and a strong negative r_s with RH, indicating that high moisture contents reduce the cover of case hardened scaling. Strong positive r_s exist with temperature and wet-dry, indicating that high temperatures and wet-dry cycles increase the cover of case hardened scaling. This result is the opposite to the results found for other forms of case hardening. Case hardened scaling was only recorded in a few instances during the survey (Figure 4.2.14), therefore, less confidence can be placed on this result.

4.2.3 REGIONAL VARIATIONS IN THE DISTRIBUTION OF SANDSTONE WEATHERING FORMS

4.2.3.1 Results

The locations of the thirty buildings selected in Chapter 4.1.2 are shown in Figure 4.2.17. These buildings show a scattered distribution along the transects, with buildings located in urban and rural areas. A few buildings just outside the transects have been included in order to ensure a scattered distribution.

Using the methodology described in Section 4.1.2, the facades of the buildings were analysed and data from 1 382 quadrats were collected. For each building the mean percentage cover (% m^{-2}) for each weathering form was collated into a data set. Exploratory analysis of the data was carried out using cluster analysis, a statistical technique which places subjects with similar characteristics into groups (Appendix 1). Therefore, buildings with similar amounts of weathering were grouped and the reasons for the resulting groups investigated. The reasons examined included: location, stone finish, distance from

obstructions, exposure to wind-driven rain and building age. Cluster analysis was carried out with data for all the weathering forms as well as with data for a few, possibly related, weathering forms, e.g. black flaking, case hardened flaking, autotrophic flaking and unaltered flaking. Therefore, in this example, factors responsible for the amount of flaking, in general, could be explored. A complete investigation of the data suggested that the only factor causing the grouping of buildings was location within the survey area. Location was found to affect the amount of black flaking, black scaling, black soiling, autotrophic flaking, autotrophic scaling and autotrophic soiling. To explain these findings the results from the various stages of the cluster analysis are discussed below. This cluster analysis only considers these six weathering forms, but very similar results were obtained when all weathering forms were analysed, or if just black flaking, black scaling and black soiling were analysed, or alternatively if just autotrophic flaking, autotrophic scaling and autotrophic soiling were analysed. This is due to variations in the latter six weathering forms being much more significant than variations in the other weathering forms.

Initially, hierarchical clustering methods were employed (Appendix 1). Three conceptually different methods, namely, unweighted arithmetic averaging technique, single linkage method and Ward's method, were used to identify the structure of the data and the number of clusters (Howard, 1991). All three hierarchical clustering methods produced similar results and suggested that three clusters exist in the data (Figure 4.2.18). A K-means cluster analysis (Appendix 1) was carried out to check the composition of the three clusters and provide a measure of distance between different members of each cluster (Table 4.2.6).

Buildings in cluster three (Figure 4.2.19) have the highest percentage cover of autotrophic flaking, autotrophic scaling and autotrophic soiling, but the lowest cover of black flaking, black scaling and black soiling. Generally, the converse is true for buildings in cluster one, while those in cluster two have intermediate values for the six weathering forms. The only exception to this pattern is the relatively high percentage cover of black flaking for buildings in cluster two (Figure 4.2.19). The net result of these differences is that buildings with low percentage cover of total blackened stone, typically have high percentage cover of total autotrophic stone and vice versa (Table 4.2.3).

Kruskal-Wallis ANOVA with ranks (Appendix 1) shows that the difference between the mean percentage cover of all six weathering forms is statistically significant for the three clusters (Table 4.2.8). This provides evidence that the percentage cover of these weathering forms does vary between clusters of buildings.

To evaluate the relationship between cluster membership and location of the buildings within the survey area, building location and cluster membership were plotted onto the survey base map (Figure 4.2.20). Buildings in cluster one, with the highest percentage of total blackened stone and the lowest percentage of total autotrophic stone, are situated in central areas of the conurbation with one exception (N1) just north of the conurbation. Members of cluster two, with an intermediate amount of total blackened stone and total autotrophic stone, are generally inside the conurbation, but also extend to the north and are skewed slightly towards the east. Members of cluster 3, with little total blackened stone, but the highest percentages of total autotrophic stone, are generally outside the conurbation or on the fringes to the east, south and west (Figure 4.2.20). This pattern suggests that urbanisation may increase the percentage cover of total blackened stone and decrease the percentage cover of total autotrophic stone.

To examine the suggested pattern further, isometric lines, representing the percentage of total blackened stone and the percentage of total autotrophic stone, were plotted onto the base map. Isometric lines were not easily delimited for total autotrophic stone, as values for individual buildings varied in a complex manner. However, isometric lines for total blackened stone were delimited (Figure 4.2.21). These isometric lines show a noticeable gradient, with values increasing from less than 10 per cent in rural areas to the west, to greater than 40 per cent in the centre of the conurbation and decreasing to less than 20 per cent in rural areas to the east. Changes from south to north are less clear, but it can be seen that in rural areas to the south, values are typically below 20 per cent, increasing in the centre to above 40 per cent, which is maintained to the north of the conurbation.

4.2.3.2 Discussion

The isometric lines of total blackened stone (Figure 4.2.21) and the cluster analysis results (Figure 4.2.20) suggest that buildings in urban areas of the West Midlands experience up to four times more total blackened stone and half the amount of total autotrophic stone than buildings in rural areas. These data are supported by observations in Italy where black soiling of sandstone was noted to be more severe in urban than in rural areas (Sabbioni and Zappia, 1992). This general pattern is complicated by local factors, exerting an influence within the conurbation. This influence is especially pronounced for total autotrophic stone and prevents accurate delimitation of isometric lines for this weathering type. However, the cluster analysis does suggest that buildings in the centre of the conurbation typically have about 11% total autotrophic stone, while those outside the conurbation have about 23%. Total autotrophic stone includes lichens, mosses and algae. The effect of atmospheric pollution inhibiting lichen growth is well documented and has been reported for sandstone buildings (Sabbioni and Zappia, 1992). Qualitative observations, during the building survey, found lichens to be the dominant autotrophic growth in rural environments. Therefore, air pollution, inhibiting lichen growth, is probably instrumental in reducing the percentage cover of total autotrophic stone in urban areas.

The isometric lines for total blackened stone show the highest cover of this weathering type occurs in an area crossing the middle of the conurbation from approximately north to south. A limb of relatively high cover also extends from the centre of the conurbation east, north of Birmingham (Figure 4.2.22). Various factors, such as relief or degree of exposure, could cause this distribution, but the most convincing factor is the historical location of industry. Major industrial emitters were identified in the 1960s by the national survey of air pollution (Warren Spring Laboratory, 1973). The location of these emitters compares closely to the isometric lines of total blackened stone (Figure 4.2.22). The central region had the most dense concentration of emitters and the limb of relatively high total blackened stone north of Birmingham has a relatively high concentration.

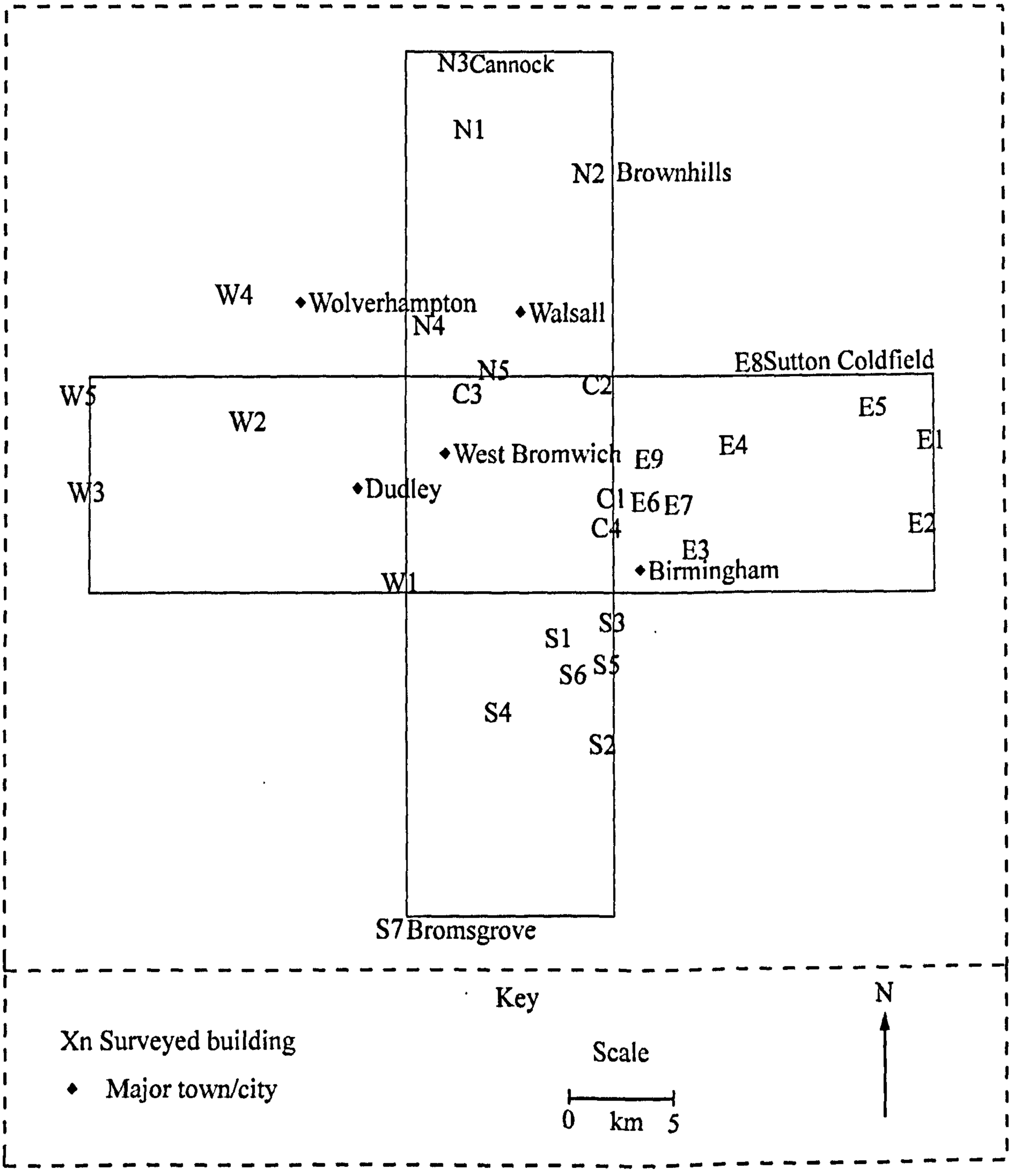

Figure 4.2.17 Location of the surveyed buildings in the sample area.

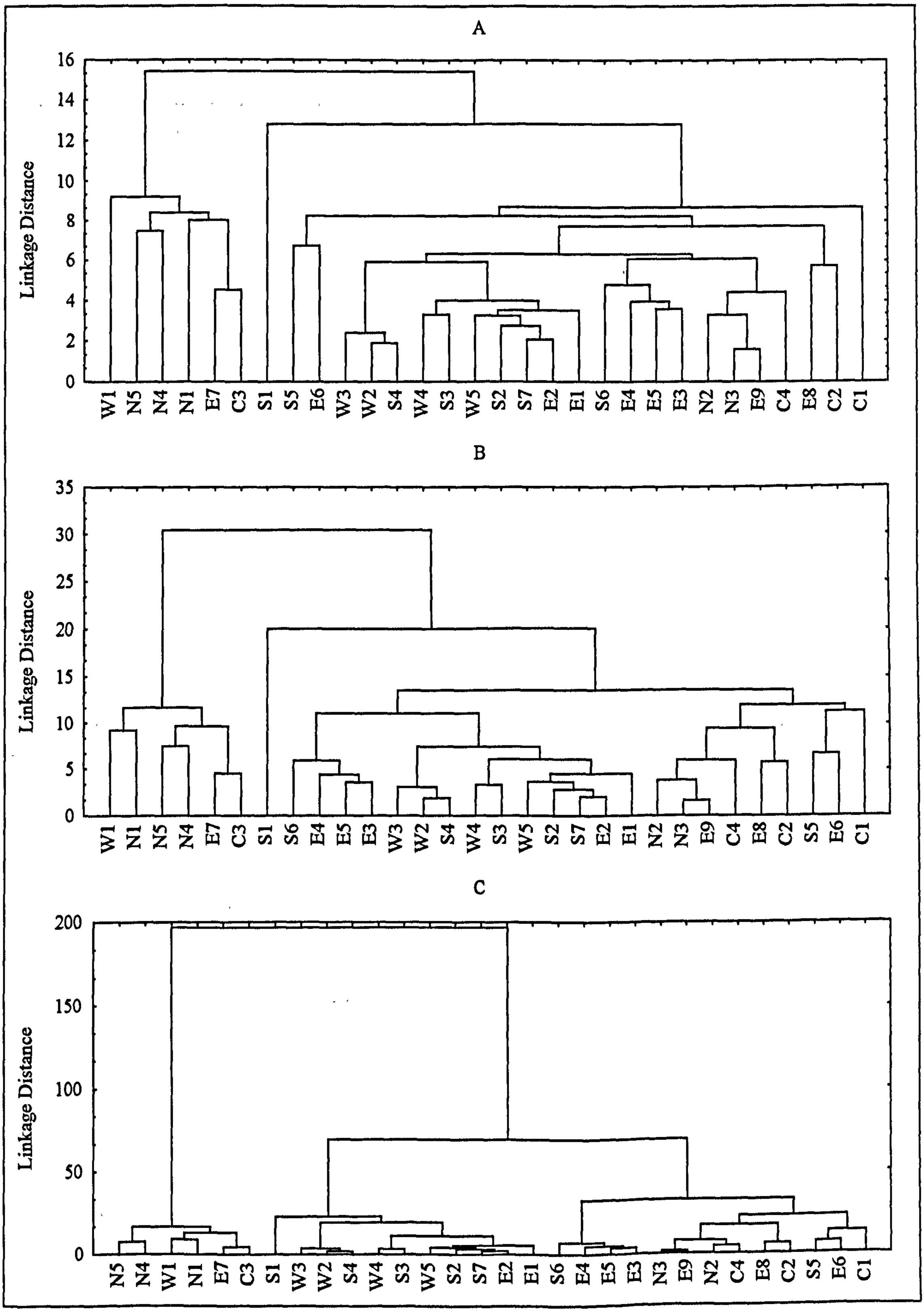

Figure 4.2.18 Dendrograms showing the results of clustering buildings by; A - single linkage, B - unweighted pair-group average and C - Ward's method. The distance measure was Euclidean.

Cluster 1		Cluster 2		Cluster 3	
Building code	Euclidean distance	Building code	Euclidean distance	Building code	Euclidean distance
C3	2.03	C1	4.03	E1	1.99
E7	1.76	C2	3.94	E2	1.73
N1	2.51	C4	3.36	S1	5.38
N4	2.85	E3	2.45	S2	0.99
N5	3.24	E4	4.30	S3	1.71
W1	3.85	E5	3.16	S4	1.84
		E6	3.19	S7	1.54
		E8	3.66	W2	1.62
		E9	1.01	W3	2.39
		N2	2.02	W4	1.89
		N3	0.92	W5	1.90
		S5	3.72		
		S6	1.96		

Table 4.2.7 Results of K-means cluster analysis. Three clusters were requested.

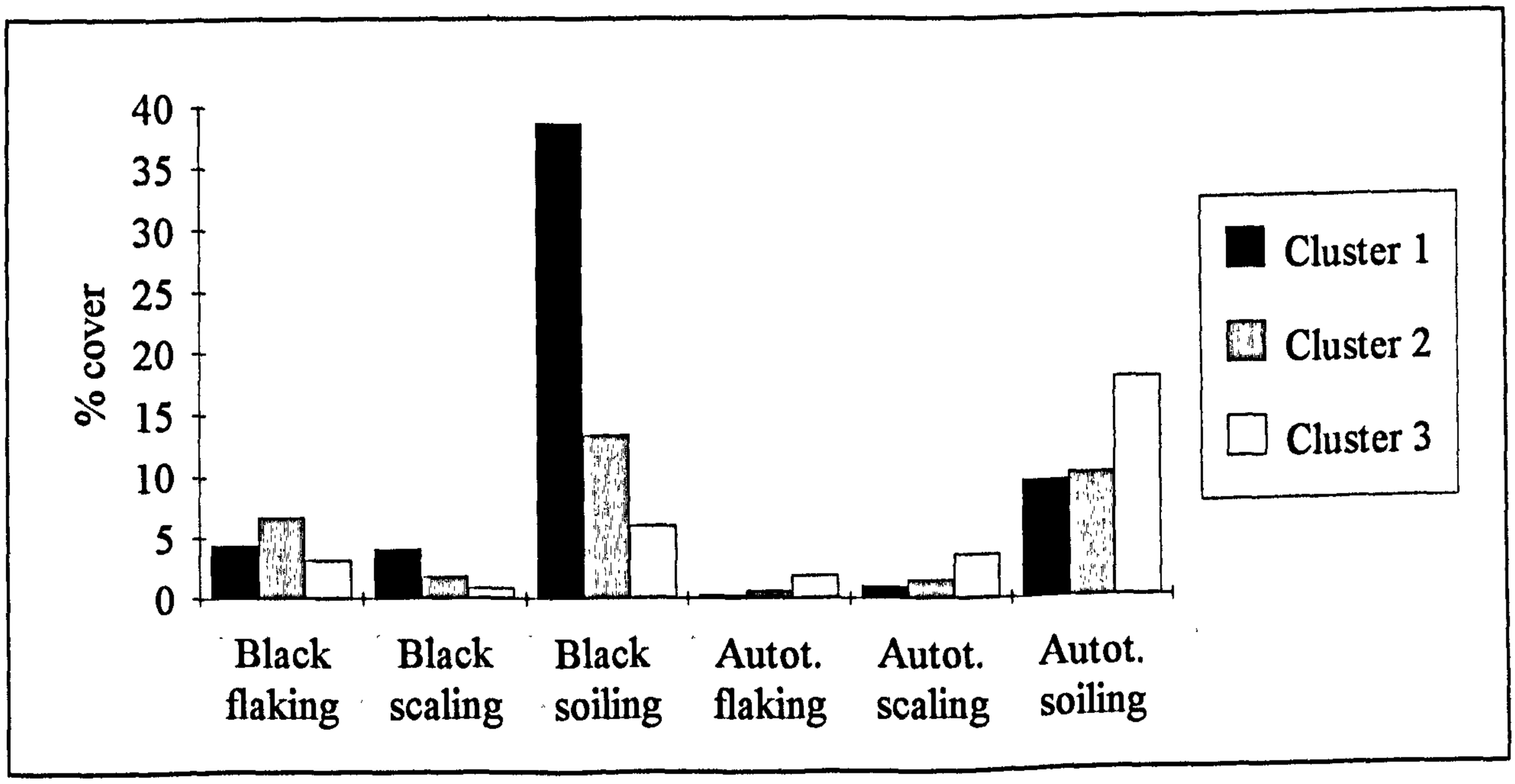

Figure 4.2.19 Mean percentage cover of each weathering form for the different clusters.

Weathering forms	Cluster 1 Mean cover (%)	Cluster 1 Standard deviation (%)	Cluster 2 Mean cover (%)	Cluster 2 Standard deviation (%)	Cluster 3 Mean cover (%)	Cluster 3 Standard deviation (%)	Kruskal -Wallis ANOVA p value
Black flaking	4.4	0.6	6.7	4.1	3.1	1.9	<0.05
Black scaling	4.1	2.8	1.8	1.0	0.8	0.7	<0.05
Black soiling	38.6	3.9	13.4	4.7	6.0	2.9	<0.01
Total blackened stone	47.0	4.9	21.9	6.5	9.9	4.6	<0.01
Autotrophic flaking	0.2	0.2	0.6	0.5	1.9	1.5	<0.01
Autotrophic scaling	1.0	1.0	1.5	1.2	3.6	1.4	<0.01
Autotrophic soiling	9.6	5.7	10.2	4.6	17.9	4.5	<0.01
Total autotrophic stone	10.9	6.4	12.4	4.5	23.4	6.2	<0.01

Table 4.2.8 Descriptive statistics and Kruskal -Wallis ANOVA for each cluster formed by K-means clustering. A p value <0.01 gives strong evidence of a difference between the means of the three clusters, whereas a p value <0.05 gives some evidence of a difference.

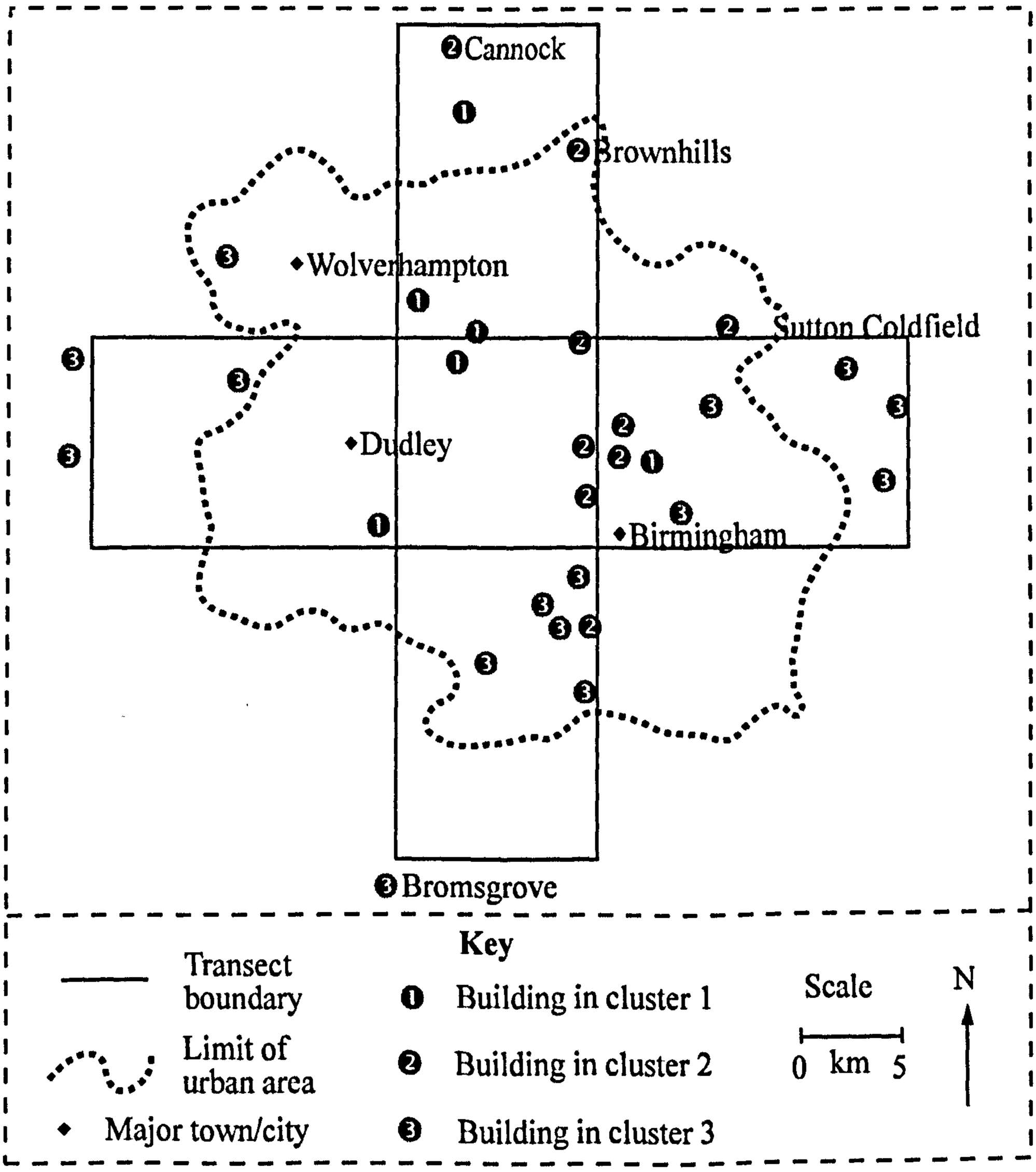

Figure 4.2.20 Map of survey area, showing transects, building distribution and cluster membership.

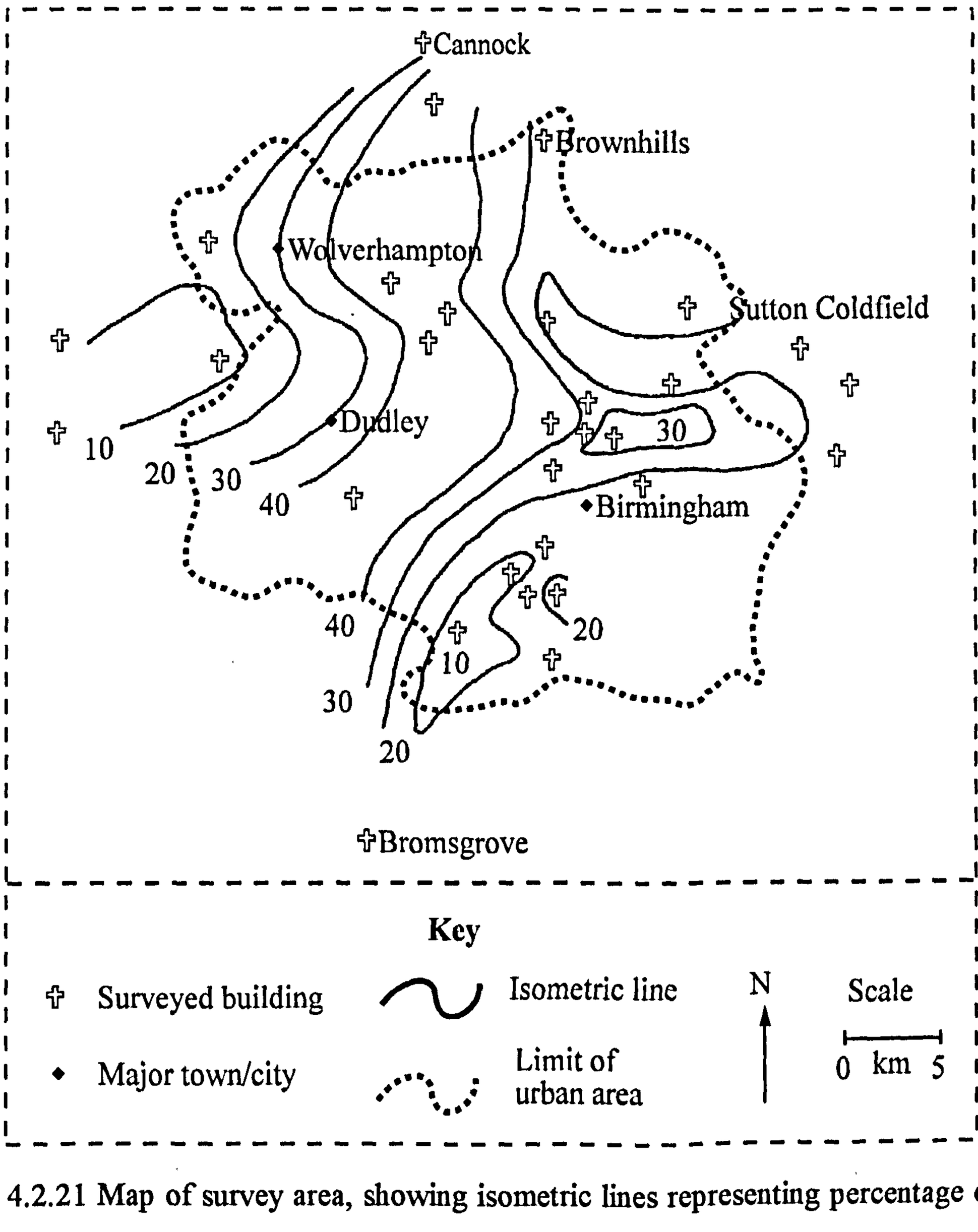

Figure 4.2.21 Map of survey area, showing isometric lines representing percentage of total blackened stone.

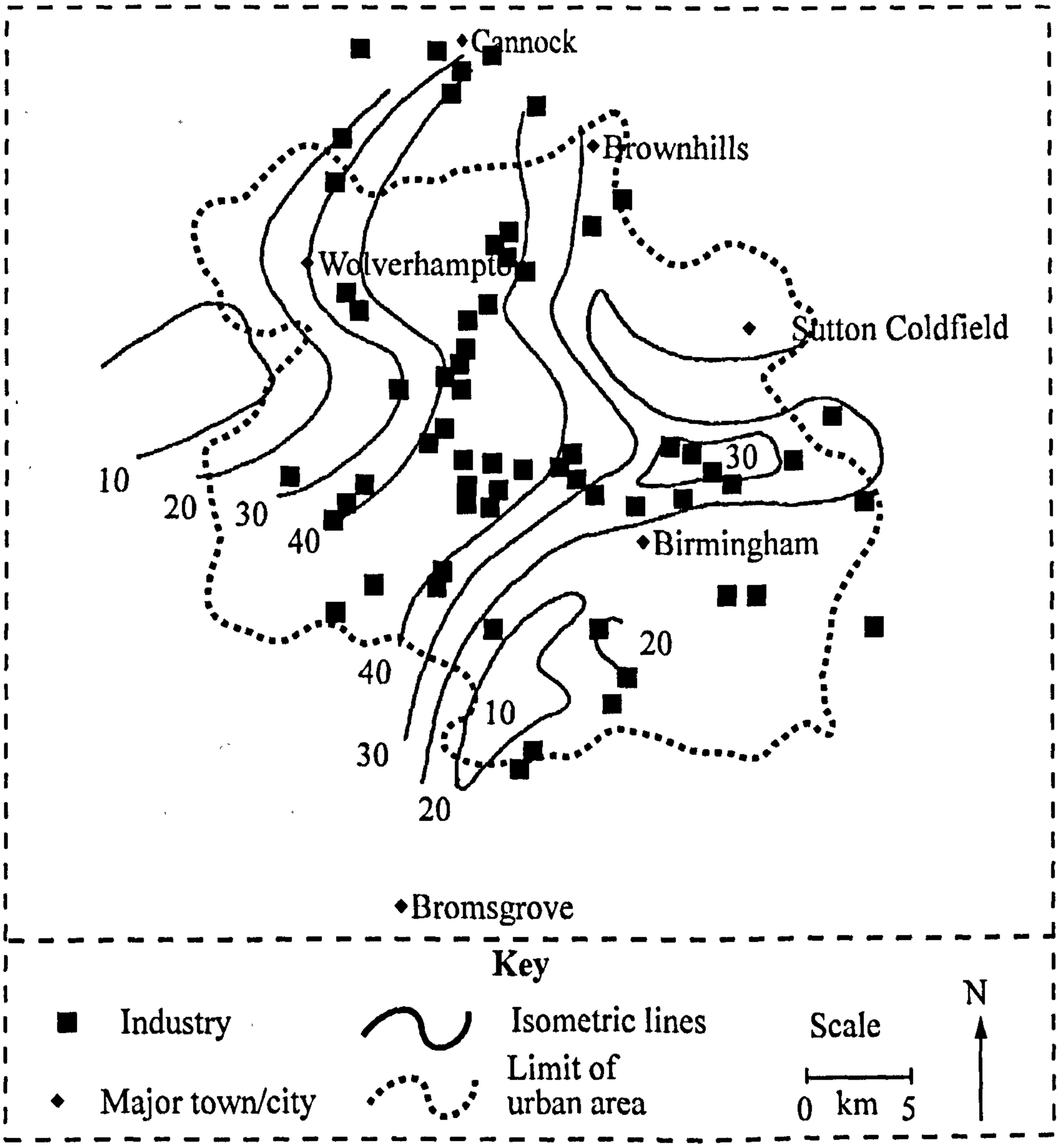

Figure 4.2.22 Map of survey area, showing the distribution of major industrial emitters identified by the national survey of air pollution 1961-1971 (Warren Spring Laboratory, 1973). The isometric lines represent the percentage of total blackened stone.

To fully explain the role of industry, and the associated air pollution, it is necessary to consider industrial locations and the type and amount of atmospheric pollutants they released for the last 150 years, the typical age of the sample of churches. Data on the latter are especially limited, and industrial locations and activities have changed over time. A survey of the conurbation in the 1940s, mapped the location of industry (Figure 4.2.23), which is thought to be a good indication of the distribution since the industrial revolution (West Midlands Group, 1948). It is noteworthy that the heavier industries, such as iron production, occupied a central location, especially between Birmingham and Wolverhampton (West Midlands Group, 1948), which may account for the highest percentage of total blackened stone occurring in this area.

The increase in total blackened stone and the decrease in total autotrophic stone, due to urbanisation and industrialisation, can be explained by the expected differences in the concentration of historical air pollution. In addition to air pollution, urbanisation alters the local climate, typically increasing air temperatures, and decreasing humidity, solar radiation and general wind speeds, although localised wind speeds may be greatly increased (Oke, 1990). It appears unlikely that these alterations are as important as increased air pollution concentrations and it may be argued that higher air temperatures, and reduced wind speed and solar radiation would increase autotrophic growth in urban areas. It is likely that the urban climate alters the deposition rates of certain pollutants on to the sandstone, as the mechanisms of pollution deposition will be altered by the local climate (Section 2.3). However, it again seems unlikely that these changes are as important as the concentration of air pollution in determining the percentage cover of total blackened stone. Nord and Tronner (1992) support this finding as they observed that black crusts were more common in the more polluted Polish cities than in Swedish cities.

4.2.4 ADDITIONAL INFLUENCES UPON THE DISTRIBUTION OF SANDSTONE WEATHERING FORMS

4.2.4.1 Results

The building survey results enable variations in weathering to be examined at various spatial scales. In addition to the macro scale (regional) and meso scale (influence of aspect), certain hypotheses about the influence of micro scale factors, upon the weathering of the sandstone, can be tested. The following hypotheses were tested with t-tests for unequal variance (Appendix 1):

a) The mean percentage cover of weathering forms for rough finished stones is equal to that for smooth finished stones.

b) The mean percentage cover of weathering forms for stone between 0.2 and 1.2 m above ground level is equal to that for stone between 1.2 and 2.2 m above ground.

Eleven* of the thirty surveyed buildings are constructed from rough finished stone and these buildings have a random distribution within the survey area. For the majority of weathering forms, smooth stone has a higher percentage cover than rough stone and this is statistically significant for six of the weathering forms (Table 4.2.8). However, rough stone does experience higher cover of black flaking, black scaling and black soiling, which results in the cover of total blackened stone being 31% for rough stone and 18% for smooth stone. This increase in total blackened stone causes the total cover of weathering to be slightly higher for rough stone (68%) than for smooth stone (61%) (Table 4.2.8).

Examination of the results assessing the influence of height above ground level show that the percentage cover of most weathering forms is greatest at the lower of the two heights (0.2 to 1.2 m) and this is statistically significant for eight weathering forms (Table 4.2.8). The only exception is black soiling, which is significantly higher at the upper height (1.2 to 2.2 m). The net effect is that total weathering is slightly higher at 0.2 to 1.2 m (67%) than at 1.2 to 2.2 m (60%) (Table 4.2.8).

* Buildings with rough finished stone are E6, N1, N2, N4, N5, S1, S5, S6, W1, W3 and W4.

The quantity of wind-driven rain received on the wall may influence the weathering of the stone. To examine this influence, Pearsons correlation coefficients have been calculated (Table 4.2.9). Correlation coefficients are close to zero, indicating that the linear relationships between wind-driven rain and percentage cover of weathering forms are not strong. Although these relationships are weak, some are statistically significant ($p<0.05$). These significant results suggest that relief weathering and unaltered scaling increase with increasing wind-driven rain, while granular disintegration, autotrophic flaking, autotrophic scaling, case hardened soiling and autotrophic soiling decrease.

4.2.4.2 Discussion

Stone finish alters the microclimate of the stone and may therefore, alter the percentage cover of weathering (Table 4.2.8). Surface roughness modifies local turbulence and substantially increases exchanges between the atmosphere and the stone (Amoroso and Fassina, 1983). Deposition of atmospheric particulates is higher on rough stones due to increased turbulence and, therefore, increased inertial impaction of atmospheric particulates. If turbulence is very high deposited particles may be re suspended, however, this is negligible for particles less than 10 μm in diameter, the optimum size for inertial impact (Amoroso and Fassina, 1983). It may be this increase in inertial impaction of atmospheric particulates that causes the significantly higher levels of black soiling and black scaling on rough finished stones than on smooth stones.

With the exception of black soiling and black scaling, other statistically significant results provide evidence that smooth stones have a higher cover of weathering forms than rough stones (Table 4.2.8). As noted above, surface roughness substantially increases exchanges between the atmosphere and the stone (Amoroso and Fassina, 1983). These exchanges include heat and moisture, as well as atmospheric particles. A rough stone has a higher surface area than a smooth stone, which increases the rate of water absorption, drying rates, heating rates and cooling rates. Consequently, rough stones may be prone to more extreme fluctuation in temperature and moisture than smooth stones. As a result weathering forms, such as granular disintegration, which require stable moisture and temperature regimes (section 4.2.3.2) have a lower percentage cover. This accounts for smooth stones having

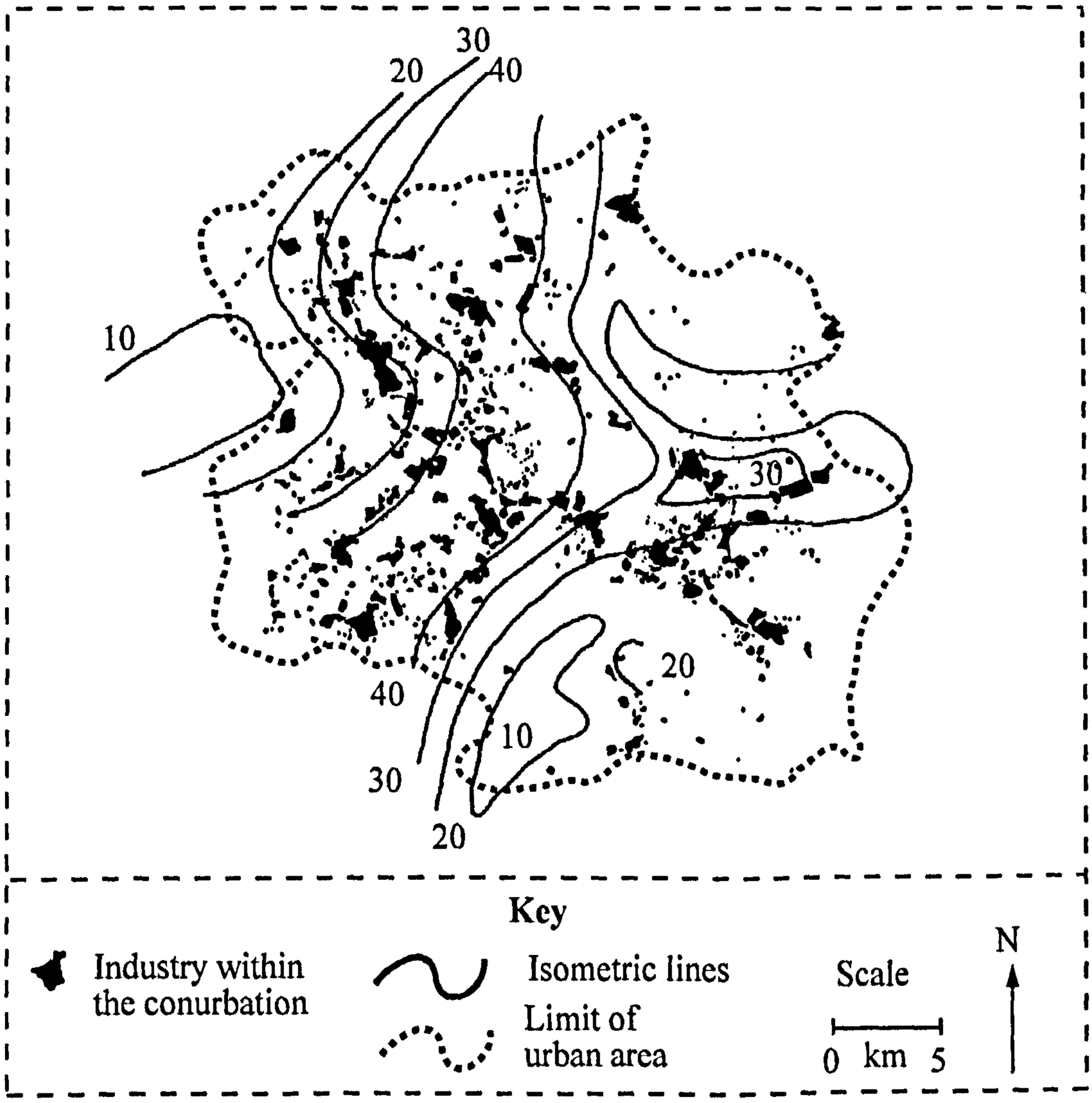

Figure 4.2.23 Map of survey area, showing the distribution of industrial areas within the conurbation in the 1940s (West Midlands Group, 1948). The isometric lines represent the per cent of total blackened stone

Weathering form	Stone finish			Height (m)		
	Rough	Smooth	p-value	0.2 to 1.2	1.2 to 2.2	p-value
Relief	**4.4**	**6.9**	**<0.01**	5.9	6.1	>0.05
Alveolar	0.1	0.1	>0.05	0.1	0.1	>0.05
Granular disintegration	**4.3**	**5.1**	**<0.01**	**5.5**	**3.9**	**<0.01**
Multiple flaking	2.2	2.7	>0.05	2.6	2.5	>0.05
Multiple scaling	**0.2**	**0.7**	**<0.01**	**0.6**	**0.3**	**<0.05**
Spalling	4.9	5.2	>0.05	**5.7**	**4.2**	**<0.01**
Black flaking	5.3	4.7	>0.05	**6.3**	**3.2**	**<0.01**
Case hardened flaking	**0.9**	**1.5**	**<0.01**	**2.0**	**0.3**	**<0.01**
Autotrophic flaking	1.0	1.1	>0.05	**1.3**	**0.7**	**<0.01**
Unaltered flaking	1.2	1.3	>0.05	**1.4**	**1.1**	**<0.05**
Black scaling	**2.6**	**1.4**	**<0.01**	1.9	1.7	>0.05
Case hardened scaling	**0.3**	**0.1**	**<0.01**	0.2	0.2	>0.05
Autotrophic scaling	2.3	2.2	>0.05	2.1	2.3	>0.05
Unaltered scaling	**2.0**	**3.1**	**<0.01**	2.6	2.8	>0.05
Black soiling	**23.1**	**11.6**	**<0.01**	**14.6**	**17.8**	**<0.01**
Case hardened soiling	**0.3**	**0.8**	**<0.01**	**1.0**	**0.1**	**<0.01**
Autotrophic soiling	13.2	12.5	>0.05	12.9	12.5	>0.05
Total	**68.2**	**60.9**	**<0.01**	**66.7**	**59.8**	**<0.01**

Table 4.2.8 The effects of stone finish and height above ground level upon the percentage cover of weathering. Statistically significant results are in bold.

Weathering form	Pearsons correlation coefficient (r)
Relief	**0.060**
Alveolar	0.019
Granular disintegration	**-0.181**
Multiple flaking	-0.021
Multiple scaling	0.001
Spalling	-0.034
Black flaking	-0.026
Case hardened flaking	-0.003
Autotrophic flaking	**-0.075**
Unaltered flaking	0.015
Black scaling	0.022
Case hardened scaling	0.037
Autotrophic scaling	**-0.113**
Unaltered scaling	**0.074**
Black soiling	-0.006
Case hardened soiling	**-0.085**
Autotrophic soiling	**-0.123**

Table 4.2.9 Pearsons correlation coefficients for per cent cover of weathering and wind-driven rain (n=1 382). Coefficients in bold are significant at $p<0.05$.

higher cover of certain weathering forms. However, heating and cooling, and wetting and drying cycles generate stress in the stone, which may be involved in the formation of certain weathering forms, such as relief weathering (Section 4.2.3.2). Therefore, it would be reasonable to expect these weathering forms to have a higher percentage cover on rough stones than on smooth stones, but the results show the opposite relationship. The distribution of stress generated by climatic cycles will be much more complex in a rough stone than in a smooth stone. Gray (1965) reports that complete constraint in all directions parallel to the surface of the stone is essential for deterioration to occur, due to internal stresses created by heating. Complete constraint may be more easily achieved in a smooth faced stone than a rough stone. In the case of rough stone, protruding parts of the surface will have very little constraint parallel to the surface (Figure 4.2.24). However, a state of semi-constraint may occur in the recesses of the stone. This constraint is not complete, as the stone parallel to the surface of the recess is unlikely to be expanding (Figure 4.2.24), as it is not heated or moistened to the same extent, as the stone at the surface. Therefore, insolation weathering and moisture cycles may be more effective for smooth stones than rough ones.

Between 0.2 and 2.2 m above ground level, height alters the percentage cover of weathering (Table 4.2.8). Eight weathering forms show significantly higher cover between 0.2 and 1.2 m than between 1.2 and 2.2 m above the ground. Increased weathering at the lower height may be due to the capillary rise of ground water. Capillary rise is influenced by climate, soil conditions, and the pore size and porosity of the stone. However, in England, capillary rise is generally limited to between a 0.5 m and 1.0 m above ground level (Oxley and Gobert, 1983). Consequently, stones between 0.2 and 1.2 m above ground level will have a higher, more stable moisture content, and a greater concentration of soluble salts, than stones between 1.2 and 2.2 m. Both of these factors were considered to increase the occurrence of granular disintegration, spalling, case hardened stone and autotrophic stone in Section 4.2.2. Therefore, the statistically significant influence of height above ground level, found for these weathering forms (Table 4.2.8), supports this observation. The reasons for multiple scaling, black flaking and unaltered flaking occurring in higher

quantities in the lower of the two zones is not clear, but it may be related to the supply of salts.

Black soiling is the only weathering form that is significantly higher between 1.2 and 2.2m than between 0.2 and 1.2 m above ground level (Table 4.2.8). However, total blackened stone is 23 per cent for both zones. This is due to a greater proportion of the total blackened stone being composed of black scaling and black flaking at the lower of the two heights (Table 4.2.8). In other words between 0.2 and 1.2 metres more of the total blackened stone is detaching. Again, this may be due to the capillary rise of water, increasing the time of wetness and soluble salt concentration.

Pearsons correlations coefficients between the percentage cover of weathering forms and wind-driven rain suggest that linear relationships are not strong (Table 4.2.9). However, it must be remembered that wind-driven rain was calculated from several factors and not measured (Section 4.1). The calculation of wind-driven rain includes several factors, such as orientation and distance from obstructions. Therefore, an increase in wind-driven rain indicates a general increase in exposure. Consequently, stones experiencing higher amounts of wind-driven rain will generally experience more variable temperature and moisture conditions. Some evidence exists to suggest that increased wind-driven rain decreases granular disintegration, autotrophic flaking, autotrophic scaling, case hardened soiling and autotrophic soiling. These weathering forms were found to be most prevalent on north and east walls (Section 4.2.2) and, therefore, supports the observation that these weathering forms are encouraged by less variable temperature and moisture conditions (Section 4.2.2). Some evidence exists to suggest the converse is true for relief and unaltered scaling, which increase with increased wind-driven rain. Again this supports the findings from Section 4.2.2, which suggest that these weathering forms are encouraged by less stable microclimates.

Distance from an obstruction, and the other factors used to assess exposure to wind-driven rain, are assessments of local conditions which influence the stone surface environment. The effect of these factors upon the weathering of the stone will be superimposed on the

influence of regional variation and the influence of aspect. This may explain, why correlation coefficients, between these factors and weathering, are not good. Although it seems reasonable that an obstruction in front of a stone will influence the weathering processes, the interactions between the many factors involved at the micro scale prevents quantification and prediction of the effect of these factors. This is not surprising due to the spatial scale at which the survey was conducted and the nature of the data collected. To quantify the effects of obstructions, more precise measurements are required, such as those conducted for the sandstone exposure trial detailed in Chapter 5.

4.3 SUMMARY

The contributions presented in this chapter, to identifying and explaining the mechanisms and weathering forms responsible for the weathering of sandstone buildings in the West Midlands, are summarised below.

a) Tensile stresses generated by the contraction phase of thermal and moisture cycles may theoretically cause fracturing of the stone.

b) Theoretically the rapid wetting of stone causes more stress than the heating or cooling of stone.

c) Aspect influences sandstone temperature, the rate and frequency of temperature changes and thermal cycles. Sandstone relative humidity, the rate and frequency of relative humidity changes and moisture cycles are also influenced by aspect. Consequently, aspect influences the level of stress imposed on the stone.

d) The occurrence of weathering forms is influenced by aspect. However, the extent and nature of this influence varies between weathering forms. Several weathering forms, such as relief weathering, show a preference for aspects with interchangeable temperature and moisture conditions. Scaling and flaking may be increased by higher temperatures which cause, salt crystallisation at depth. Blackening of the stone is increased on aspects experiencing frequent wetting-drying cycles and wind-driven rain. Other weathering forms, such as autotrophic soiling, show a preference for less variable temperature and moisture

conditions. Granular disintegration, spalling and case hardening are increased where drying occurs slowly at the surface of the stone.

e) Buildings in urban areas experience up to four times more blackened stone and half the amount of autotrophic stone, than those in rural areas. The historic location of industry is important in determining the occurrence of these weathering types.

f) Stone finish influences weathering, with smooth stones typically having more weathering than rough ones. This may be due to the increased effectiveness of thermal and moisture cycles for smooth stones. Total blackened stone has a greater occurrence on rough stones, possibly due to increased atmospheric deposition caused by inertial impact.

g) More weathering occurs between 0.2 and 1.2 m above ground, than between 1.2 and 2.2 m. This may be due to the increased capillary rise of water below 1.2 m, which increases salt concentrations and the time of wetness.

h) The correlation between weathering and exposure to wind-driven rain is poor, however, statistically significant correlations do exist for relief weathering, granular disintegration, autotrophic flaking, autotrophic scaling, autotrophic soiling, unaltered scaling and case hardened soiling.

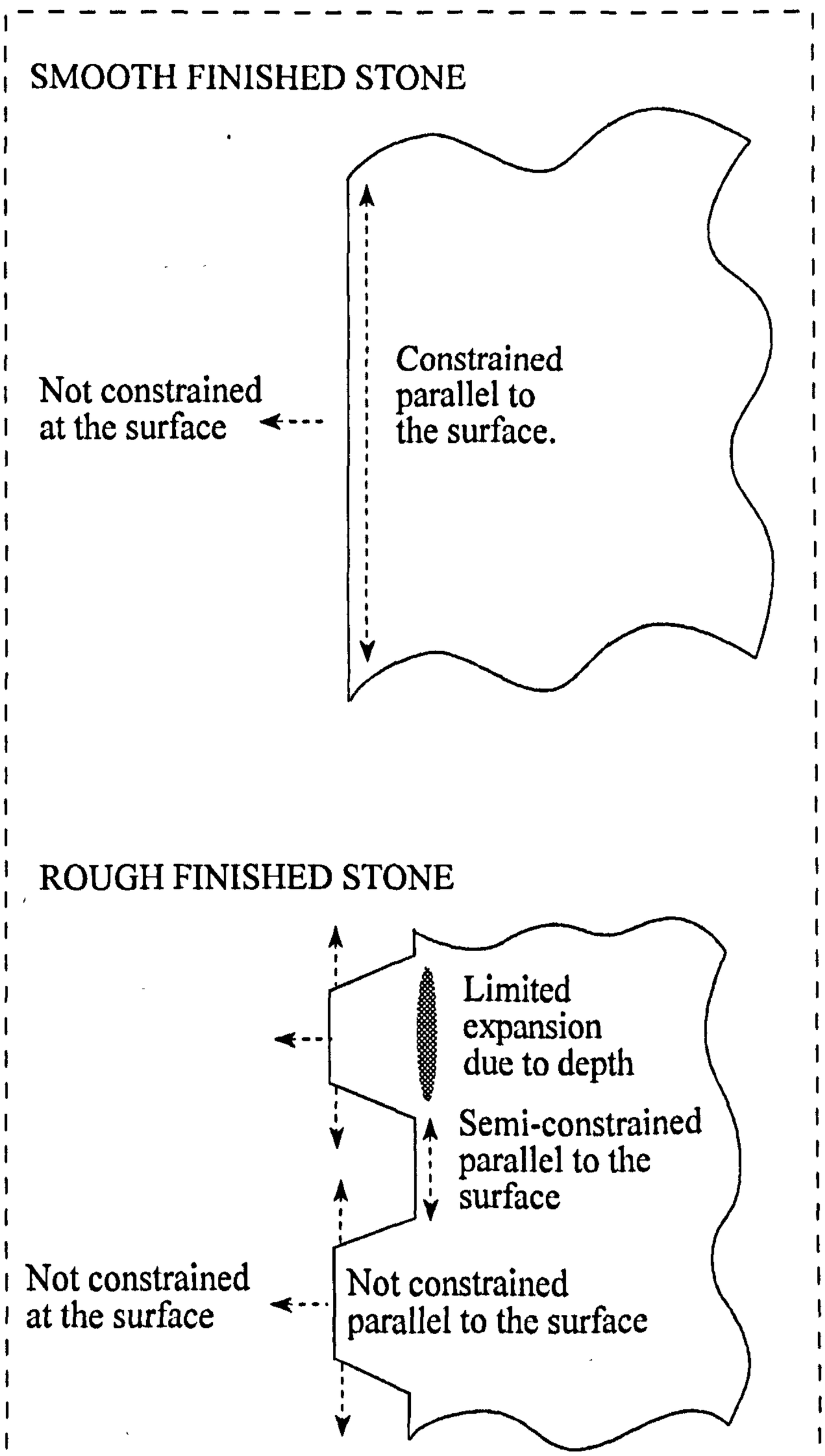

Figure 4.2.24 Simplified diagram of the distribution of stress due to a temperature or moisture increase in a smooth and rough finished stone.

CHAPTER 5

CHEMICAL ALTERATIONS DUE TO SANDSTONE WEATHERING

As detailed in Section 3.2, five experiments were selected to identify and explain the weathering mechanisms responsible for the weathering of sandstone buildings in the West Midlands. In this chapter, experiments analysing the chemical alteration of weathered sandstone, will be considered. These involve a microcatchment experiment, an exposure trial and the analysis of weathered stone collected from several buildings. A preliminary discussion of the results from these experiments is presented in this chapter. The findings presented in Chapter 4 and in this chapter are considered in more detail in Chapter 6 to elucidate the mechanisms causing the weathering of sandstone.

5.1 METHODOLOGY

5.1.1 MICROCATCHMENT EXPERIMENT

In this investigation, six microcatchments were constructed from 5 mm thick perspex, as shown in Figure 5.1.1. Three were fitted with 50 mm thick slabs of Mottled Hollington Sandstone, while the others were fitted with roughened glass as a control. The slabs were cut from a single block of stone using a water cooled diamond saw. They were placed in the microcatchments and their sides sealed with silicon sealant to prevent water seepage along the edges of the stone. Mottled Hollington Sandstone, a medium grained ferruginous Triassic Sandstone, was selected because it is widely used in Central England, including some notable buildings such as Coventry Cathedral. The stone was obtained from J. Oldham Ltd., Great Gate Quarry, Staffordshire. Its chemical composition was determined using a Fisons ARL 8410 X-ray Fluorescence Spectrometer (XRF) (Table 5.1.1) and petrologic description of the stone was determined from thin sections (Table 5.1.2).

Three microcatchments were fitted with a glass surface as a control. The 4 mm thick glass plates were first roughened by sandblasting and then glued to a polystyrene slab to make a total thickness of 50 mm, the same as the sandstone slabs. Glass was used as a control surface because previous research by Cooper *et al.* (1992) found it to be more suitable than either perspex or copper surfaces. Tests for water solubility were carried out on some of

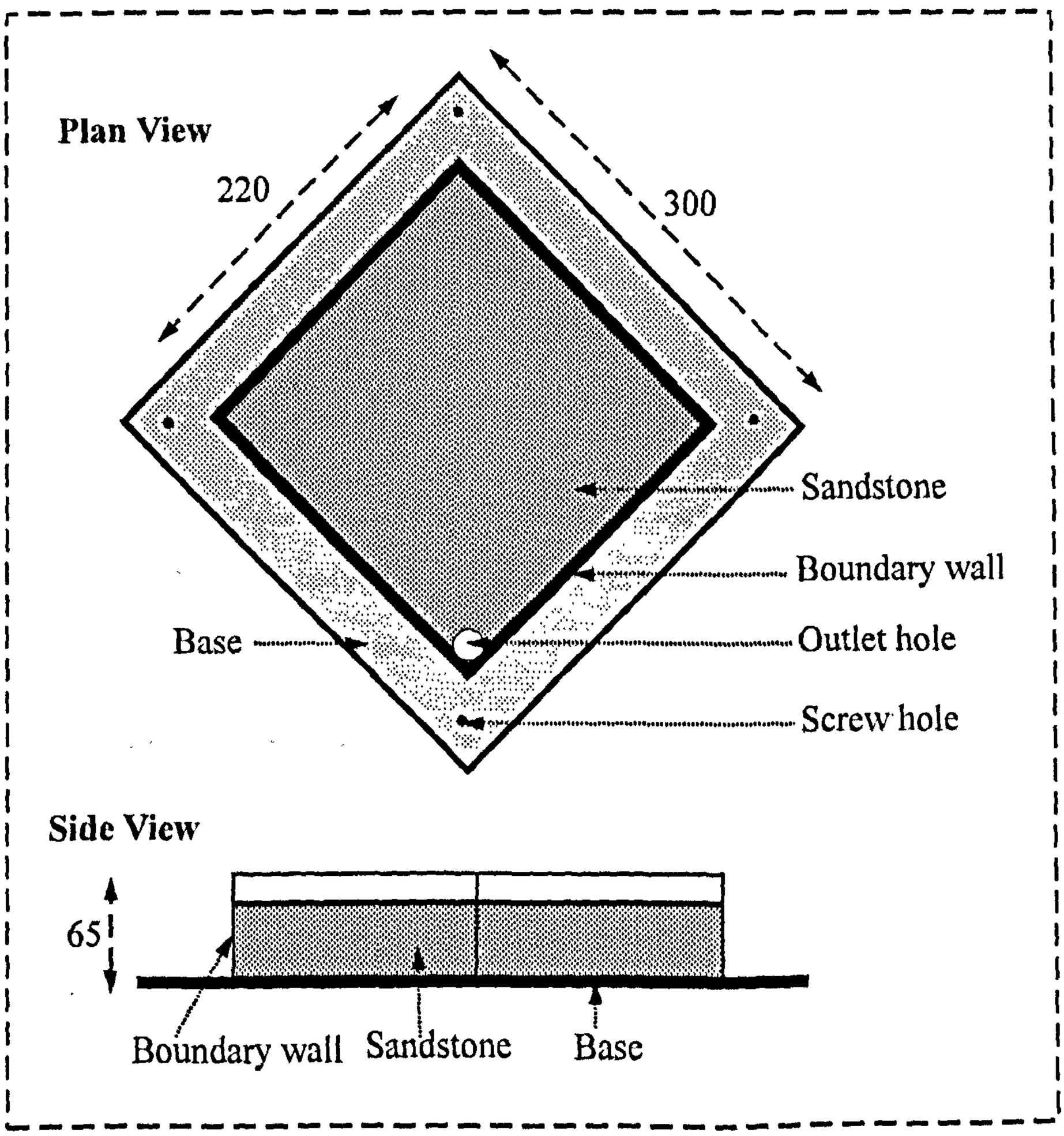

Figure 5.1.1. Microcatchment design (all dimensions in mm).

Major elements (%)		Minor elements (ppm)	
SiO_2	86.2279	As (ppm)	9
TiO_2	0.1447	Ba	483
Al_2O_3	7.2850	Ce	223
Fe_2O_3 (total)	1.4296	Cr	584
MnO	0.0249	Cu	106
MgO	0.9634	F	887
CaO	0.0606	Ga	15
Na_2O	0.2507	Nb	26
K_2O	2.4119	Nd	35
P_2O_5	0.0506	Ni	259
CO_2	0.0004	Pb	50
S	0.1417	Rb	242
Cl	0.0310	Sr	139
		V	37
		Zr	525
	TOTAL (%)	99.3844	

Table 5.1.1. Chemical composition of Mottled Hollington Sandstone. Mean values (n=5) expressed as per cent oxide by weight.

Identification	Hollington Sandstone, Hollington Formation, Sherwood Sandstone Group, Triassic (Charsley, 1982). Formerly called Lower Keuper Sandstone. Collected from J. Oldham, Great Gate Quarry, Staffordshire (NGR SK05524020).
Classification	Quartz Arenite
Texture	Grain size distribution is that of a very well sorted medium grained sand. Grains are angular to sub rounded, but dominantly sub angular. There is high inter-granular porosity, with voids differing greatly in size. However, some concave-convex contacts between quartz grains are present. Hollington is texturally mature.
Mineralogy	Quartz is dominant, mostly monocrystalline, but also polycrystalline is separable. Some rock fragments especially chert, are present. Traces of muscovite, biotite, orthoclase, plagioclase and microcline are evident. A thin layer of hematite coats most grains and some small patches of localised calcite cement can be found.

Table 5.1.2. Petrographic report for Mottled Hollington Sandstone used in the microcatchment experiment.

the materials used to construct the microcatchments, by shaking two grams of each material in 50 ml of distilled water for 30 minutes. Subsequent multi-element analysis of the leachate, using a Thermo Jarrell Ash Plasma - 300 Inductively Coupled Plasma Spectrometer (ICP), suggested that these materials would not interfere with the experiment (Table 5.1.3).

The six microcatchments were installed on the 28th September 1993 at the University of Wolverhampton Urban Meteorological Station, located on a roof top site in Wolverhampton town centre (NGR SO915988) (Plate 5.1.1). The microcatchments were attached to the South West facing parapet at a fifteen degree angle to the horizontal, with the corner housing the plastic discharge tube at the lowest point. The parapet was covered with 'Astro Turf' to reduce raindrop splash. The stone and glass units were arranged alternatively and the discharge tube from each unit was fed to an individual polyethylene bottle through a water tight seal. The collecting bottles were housed in an insulated box, in order to reduce algae growth, to minimise changes in sample temperature, which could otherwise affect solubility, and to limit sample evaporation, which would increase the concentration of the solution.

Runoff from the microcatchments was collected weekly, provided that at least 50 ml of runoff had occurred. All equipment coming into contact with the samples was thoroughly cleaned and rinsed with deionised water. The volume and pH (using a Whatman PHA 220 pH Meter) were measured and the samples filtered in preparation for chemical analysis. If the samples were less than 100 ml the entire sample was filtered. When more than 100 ml was present the sample was shaken and the first and last 50 ml extracted from the collecting bottle was filtered. Filtering larger volumes of samples caused the blockage of the filter membranes. Forty-seven millimetre diameter Whatman Cellulose Nitrate Membranes, with a 0.45 μm pore size, the standard for water analysis (Hunt and Wilson, 1986), were selected. Before filtering the filters were marked with a graphite pencil, dried at 105^{o}C to a constant weight and weighed to an accuracy of 0.1 mg. The same procedure was used for drying filters after filtration of runoff samples. The mass of the filter before filtration was subtracted to give the mass of the filterable component in the sample.

Water solubility (mg kg^{-1})	Glass	Silicon Sealant	Epoxy Resin
Ca^{2+}	0.00	0.00	0.00
Cl^-	8.33	ND	ND
Mg^{2+}	2.43	0.00	0.00
K^+	2.67	0.00	0.00
Si^+	46.37	0.00	0.00
Na^+	33.00	23.26	0.00
SO_4^{2-}	16.67	20.94	92.31
Zn^{2+}	0.00	2.33	0.00

Table 5.1.3. Amount of water soluble material contained in the microcatchment construction materials (mg kg^{-1}) (ND - not determined).

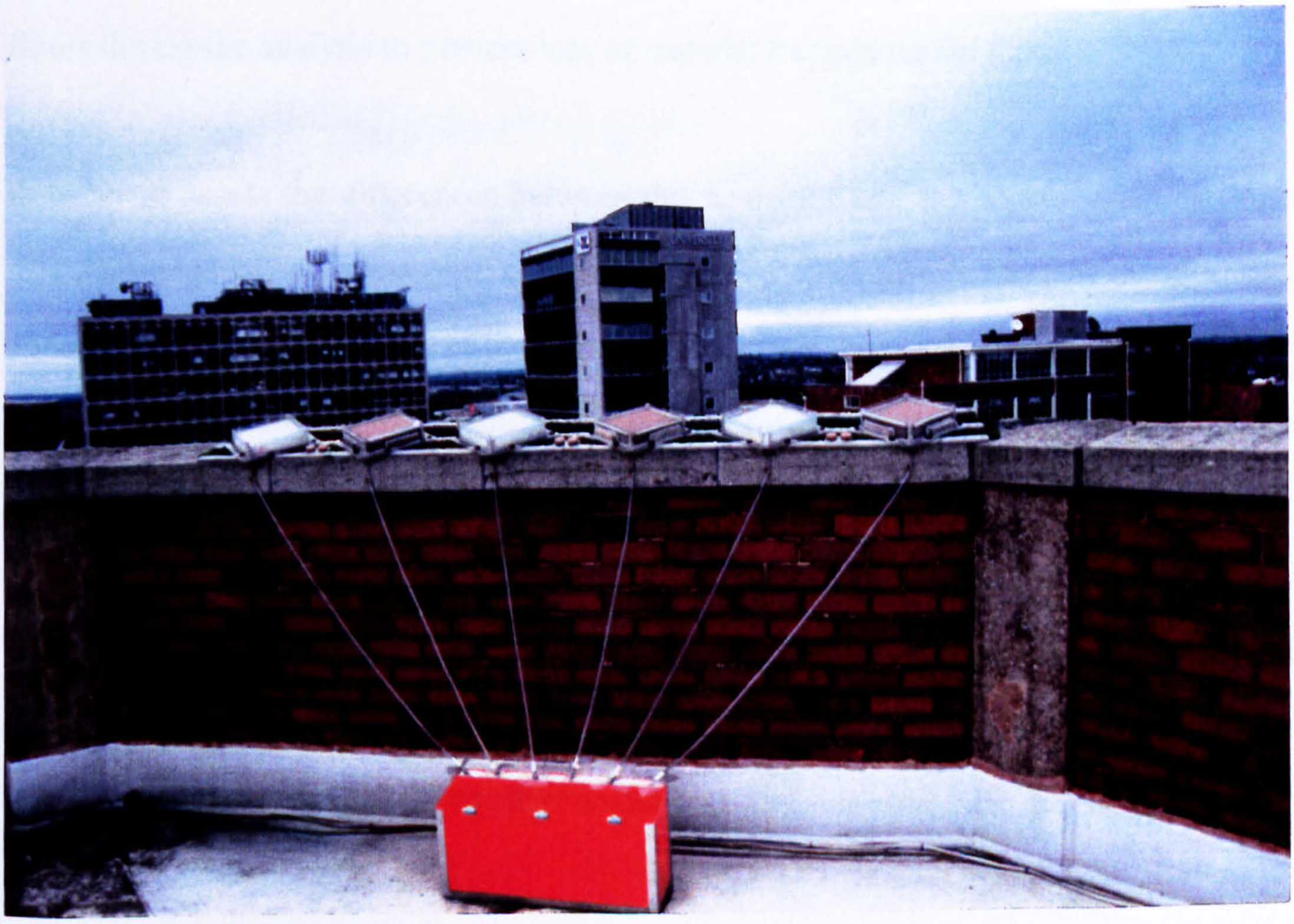

Plate 5.1.1. Microcatchment experiment at the University of Wolverhampton, Urban Meteorological Station.

The filtrates were analysed for chloride, sulphate and nitrate anions, using a Dionex DX-100 Ion Chromatograph (IC), while potassium was determined with a Varian AA-75 Atomic Absorption Spectrometer (AA). Twelve other elements were determined using a Thermo Jarrell Ash Plasma-300 Inductively Coupled Plasma Spectrometer (ICP). Quantitative elemental analysis was carried out on the filters, using a Fisons ARL 8410 X-ray Fluorescence Spectrometer (XRF). The Whatman Cellulose Nitrate filter membranes were found to have very low background concentrations when analysed with XRF. The program was calibrated on standards prepared by impregnating filters, from the same batch as those used for this experiment, with known weights of XRF soil standards. These soil standards (SO-1 to SO-4) had a known chemical composition (Appendix 5). Impregnation of the filters was achieved by placing a damp membrane in a filter funnel and evenly sprinkling the XRF standard onto the filter. Pressure created by a vacuum pump carried the standards onto the filter and these remained in place when dried. Mylar film was placed over the filters during the analysis to prevent loss of material trapped on the filter.

In order to assess the differences between the sandstone and the control microcatchments, cumulative losses and gains were calculated in mg m^{-2}, for particulate and chemical species under consideration. This was derived by subtracting the weekly values obtained for the three glass microcatchments from those obtained for the three sandstone microcatchments to give three results in milligrams. These were averaged and multiplied by 20.66 to standardise them to a sandstone slab one metre square and five centimetres thick (Equation 5.1.1). The results for each week were then added to the previous weeks to give cumulative losses and gains. To test the statistical significance of the calculated differences, paired t-tests were applied to the weekly results obtained for glass and sandstone microcatchments.

$$\text{Weekly value (mg m}^{-2}\text{)} = \frac{((\text{Stone 1-Control 1}) + (\text{Stone 2-Control 2}) + (\text{Stone 3-Control 3}))}{3} \times 20.66$$

Equation 5.1.1

5.1.2 SANDSTONE EXPOSURE TRIAL

In this experiment, the sample preparation and exposure system applied to limestone by Whalley, B *et al.* (1992) was modified. The sandstone samples were in the form of discs (38 mm diameter), cut with a water cooled diamond core drill from a single block of Mottled Hollington Sandstone. The cores were trimmed to a 10 mm thickness with a dry diamond saw and glued to 25 mm aluminium Scanning Electron Microscope (SEM) stubs, with 'Araldite' epoxy resin. Before use, the epoxy resin was tested for water solubility according to the procedure detailed in Section 5.1.1. Results suggested that epoxy resin would not interfere with the experiment (Table 5.1.3). To identify each sample and to indicate the exposure duration and analysis required, the SEM stubs were permanently labelled on their underside. The blocks of stone used for these samples were petrographically and chemically very similar to that used for the microcatchment experiment (Table 5.1.1) and (Table 5.1.4). Analysis of thin sections revealed that the stone used for this trial was slightly more compact and had more hematite cement than that used for the microcatchments (Table 5.1.2).

Two exposure racks were constructed to hold nine samples in an exposed position and nine in a sheltered position. This was achieved by a two tier system which held all samples at an angle fifteen degrees to the horizontal and facing South West. Identical racks were placed at Preston Montford Field Studies Centre and Winterbourne Meteorological Station on 20th and 21st October 1993, respectively. Winterbourne (NGR SP052820) is 4 km South West of Birmingham city centre and forms part of the University of Birmingham campus. The site is surrounded by medium density housing, whereas Preston Montford (NGR SJ431142) is a rural site, situated 6 km North West of Shrewsbury, Shropshire. The two sites were selected as meteorological data were available at both locations and the different surroundings would highlight any contrasts in weathering between urban and rural locations. The rack at Birmingham was positioned at approximately 1.5 m above ground level in an open area (Plate 5.1.2), whilst it was necessary to place the rack at Preston Montford on the roof of a single story building to obtain a similar degree of exposure to that at Birmingham (Plate 5.1.3).

To explain the labels given to the stubs, **BT1A** will be used as an example. **B** indicates Birmingham rack, **T** indicates Top shelf, **1** indicates hole number 1 on that shelf and **A** refers to the duration of exposure and the analysis required. The positioning of the stubs on each of the shelves was standardised using a latin square design. Also, if it is considered that the position of the stub on the shelves influences the results, then the latin square design enables this to be analysed with Analysis of Variance (Appendix 1). The resulting position of the stubs on each of the four shelves and the analysis given to each stub is shown in Figure 5.1.2.

Energy Dispersive Analysis by X-ray (EDAX) was initially selected for elemental analysis, since unlike destructive forms of testing, it enables analysis of the same area of stone before and after exposure. However, initial analysis of the samples indicated that EDAX was not ideally suited to this application. This was partly due to the titanium and barium peaks appearing in a similar place on the EDAX spectra and as a consequence these two elements could not be differentiated. Titanium is often used in weathering studies to calculate weathering indices because it is a very stable element, which is generally less affected by weathering. Furthermore, the limits of detection for many elements was not considered sufficient to enable the effects of short term exposure to be measured. Due to these limitations a non-destructive technique, using X-ray Fluorescence Spectrometry (XRF) on a Fisons ARL 8410 X-ray Fluorescence Spectrometer was found most suitable. The samples were inserted directly into the ARL cassettes and analysed using a programme calibrated on geochemistry standards (Appendix 5), written by Dr. C. Williams, University of Wolverhampton. The programme was run three times on each sample and mean elemental concentrations and standard deviations were recorded. Three control samples (CA-CC) were kept unexposed as reference disks. These were analysed with the samples before and after exposure. For each element, the results for the control samples from the second analysis (i.e. when the samples had been exposed) were divided by those for the first analysis (i.e. before the samples had been exposed) to give a conversion factor. These factors were multiplied by the results from the first analysis to account for any effects of instrument instability.

Major elements (%)		Minor elements (ppm)	
SiO_2	82.9488	As (ppm)	9
TiO_2	0.1674	Ba	3208
Al_2O_3	7.2910	Ce	114
Fe_2O_3 (total)	1.5767	Cr	548
MnO	0.0267	Cu	87
MgO	0.9280	F	695
CaO	0.0617	Ga	9
Na_2O	0.2500	Nb	21
K_2O	2.6184	Nd	28
P_2O_5	0.0522	Ni	246
CO_2	0.0003	Pb	32
S	0.1932	Rb	889
Cl	0.0220	Sr	862
		V	99
		Zr	529
TOTAL (%)	96.8740		

Table 5.1.4. Composition of Mottled Hollington Sandstone used for the Birmingham and Preston Montford racks, expressed as per cent oxide (by weight).

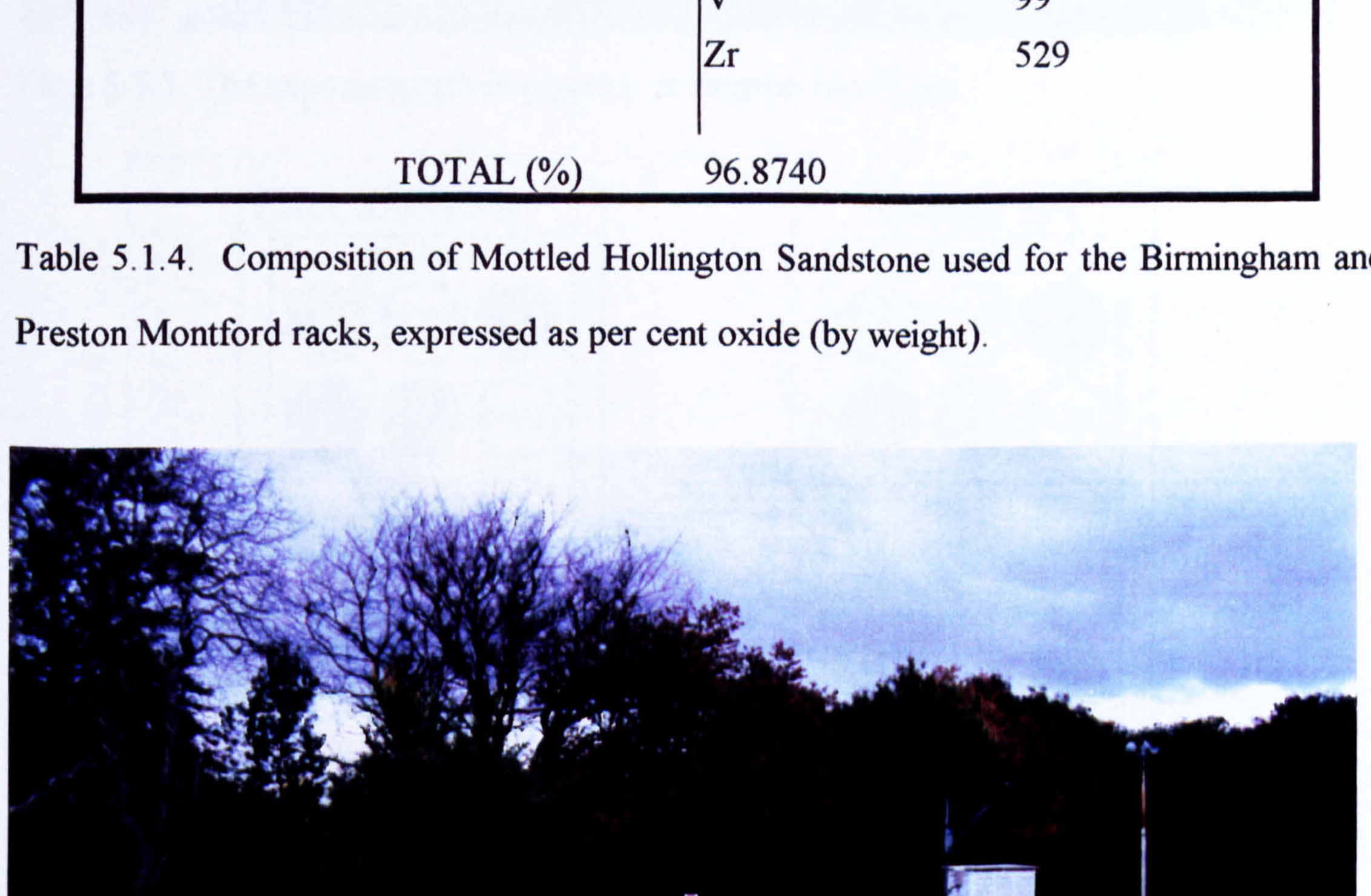

Plate 5.1.2. The exposure rack in position (centre of photograph) at Winterbourne.

Plate 5.1.3. The exposure rack in position at Preston Montford.

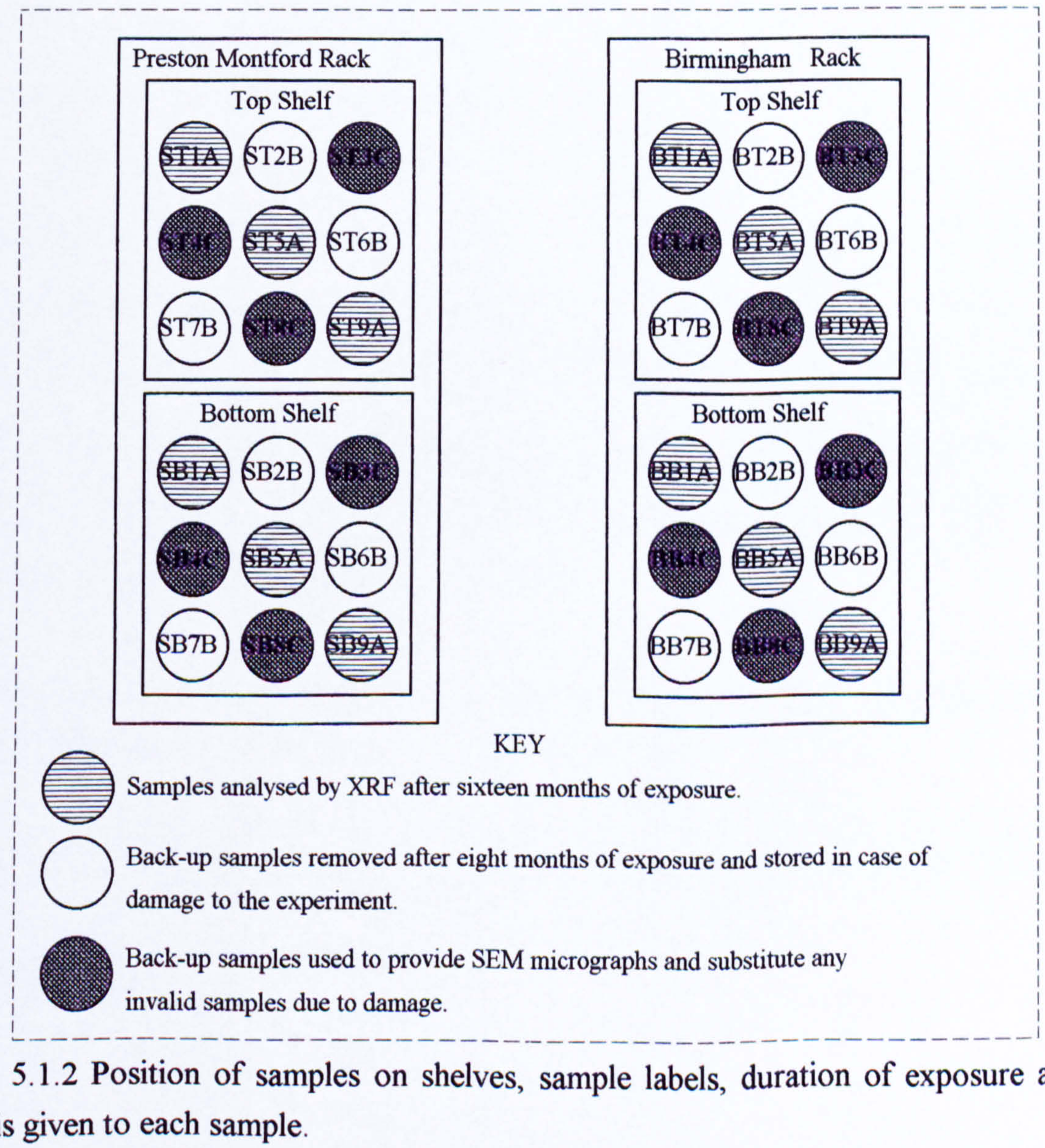

Figure 5.1.2 Position of samples on shelves, sample labels, duration of exposure and the analysis given to each sample.

Although the standard deviations indicated acceptable accuracy for most elements, upon conversion to oxides, it was found that the total percentage of constituents identified was around 80%. Although organic material and structured water were not included in this total, it appeared low, so the technique was checked. The calibration was found to be correct, but when three samples of the same stone were prepared using the compressed powdered disc technique (the same technique used for the preparation of the calibration standards), rather than a stone disc, the sum of the analysis was close to 100%. This indicated that the discrepancy was caused by differences between the samples structure and that of the calibration standards. This was due to the compressed powder discs being dense, very homogeneous and smooth (a finely divided sample is compressed with a binding wax to give a smooth disc), whereas the cut rock faces were less homogeneous and porous. These differences alter the properties of the X-ray back scatter and hence the final concentrations. To account for this discrepancy conversion factors were calculated for each element. This was achieved by dividing the results for three compressed powdered samples (RA-RC) by the results for the sandstone control discs (CA-CC) to give a conversion factor. This factor was multiplied by the concentration before and after exposure to account for the structural effects of the stone. So when samples were analysed the results were corrected for the effect of the structure of the stone and changes in instrument stability (Equations 5.1.2 to 5.1.3). Once these corrections had been made the results before exposure were subtracted from those after exposure to give elemental changes (Equation 5.1.4). The effects of location and shelter upon these changes were assessed with Two Way Analysis of Variance, with replication (Appendix 1).

Step One. The XRF results for the samples before they were exposed are corrected for the affects of the structure of the stone and instrument instability.

$$c[X_1] = [X_1] \times \left(\frac{((CA[X_2] + CB[X_2] + CC[X_2]) / 3)}{((CA[X_1] + CB[X_1] + CC[X_1]) / 3)}\right) \times \left(\frac{((RA[X_2] + RB[X_2] + RC[X_2]) / 3)}{((CA[X_2] + CB[X_2] + CC[X_2]) / 3)}\right)$$

Equation 5.1.2

Step Two. The XRF results for the samples after exposure are corrected for the affects of the structure of the stone.

$$c[X2] = [X2] \times \left(\frac{((RA[X2] + RB[X2] + RC[X2]) / 3)}{((CA[X2] + CB[X2] + CC[X2]) / 3)} \right)$$

Equation 5.1.3

Step Three. The actual amount of change (ppm) is calculated.

$$AC = c[X2] - c[X1]$$

Equation 5.1.4

Where

c	=	Corrected
[Xn]	=	Concentration for element X on the nth analysis (ppm)
CA to CC	=	Control disks
RA to RC	=	Reference disks
AC	=	Actual change (ppm)

A Phillips 515 Scanning Electron Microscope (SEM) was used to monitor micro-morphological changes of the stone due to weathering. This was achieved by comparing unexposed control samples with samples that had been exposed for sixteen months. A thin gold coat was applied to the surface of the specimens, which prevented the build up of an electron charge and hence distortion of the image. Therefore, samples used for SEM analysis could not be used for XRF analysis due to this gold coat. It was also inappropriate to use samples already analysed by XRF for SEM micrographs, as the vacuum applied to the sample during XRF altered the distribution of deposited particles on the sample.

5.1.3 ANALYSIS OF SAMPLES FROM BUILDINGS

During the survey permission was granted to remove stone that was detaching from ten of the buildings*. Forty six samples were collected and the form of weathering causing detachment recorded. The samples were dried at 105°C and tested for soluble salts using

* Samples were collected from the following buildings: C1, C3, C4, E3, E4, E6, S1, S7, W3 and W4.

the method prepared by Ciabach and Skibinski (1989). This involved a portion of the samples being crushed with a mortar and pestle to pass through a 0.125 mm sieve. The crushed samples were dried to a constant weight, and 1 g of the samples were weighed to an accuracy of 0.1 mg. These were placed into conical flasks and lightly shaken for one hour in 10 cm^3 of deionised water. The emulsions were filtered through Whatman 44 filter papers by decantation. The flasks and the filter papers were rinsed twice with 5 cm^3 of distilled water and the sediments subjected to extraction for a second time. The filtrates were tested for chloride, sulphate and nitrate anions by IC, while potassium was determined by AA. Twelve other elements were determined using ICP. From the results of the analysis the concentrations (ppm) of each of the extracted ions in the original samples were calculated.

The above procedure only removes soluble components from the samples, giving little information on any insoluble elements that may be involved in the soiling of the sandstone. To evaluate these elements, the remainder of the samples were milled, prepared as supported samples in a Mylar sandwich and analysed with XRF. The XRF program was calibrated on geochemistry standards (Appendix 5) and ran three times on each sample, giving mean elemental concentrations and standard deviations. Using the method described by Sabbioni and Zappia (1992) enrichment factors (EF Rock) were calculated for each element (Equation 5.1.5).

$$\text{EF Rock X} = \frac{(X / Ti)\ \text{weathered stone}}{(X / Ti)\ \text{unweathered stone}}$$

Where X = is the concentration of the element X
Ti = is the concentration of titanium

Equation 5.1.5

Elemental concentrations for unweathered stone were obtained from Pettijohn (1963) who reports the average chemical composition of sandstones, based on the analysis of 371 American sandstones used in building. Pettijohn (1963) fails to provide results for some trace elements and in those cases the average concentrations found for Hollington Sandstone were used.

5.2 RESULTS AND DISCUSSION

5.2.1 ATMOSPHERIC DEPOSITION

For the first nine weeks of the microcatchment experiment (28.9.93 - 30.11.93), the loss of particulate matter from Hollington Sandstone was found to be relatively constant (Figure 5.2.1), with a mean weekly particulate loss of 128 mg m^{-2} $week^{-1}$. Analysis of these data, using a paired t-test, showed the loss of particulate matter to be statistically significant ($p<0.05$). This loss was positively correlated with weekly precipitation volume with a Pearsons correlation coefficient of 0.98. The most likely explanation for this initial loss is the loosening of sandstone grains during the cutting of the stone, which are then detached by raindrop impact. This is supported by SEM and EDAX analysis of the filter membranes which showed sandstone grains to be present. Since this initial loss, there was a statistically significant ($p<0.05$) uptake of particulate matter by the sandstone (Figure 5.2.1). This uptake may have been due to the porous nature of the stone, trapping atmospheric particles within its structure.

To obtain more information on the nature and source of the particulate matter accumulating on the sandstone, the results from XRF analysis of the filter membranes were examined. It would be expected that the graph for the sum of elements occurring as particulate matter (simply the sum of elemental changes detected by XRF of the filter membranes) would be similar to that for total particulate matter. This was not the case (Figure 5.2.1) probably due to initial problems with the analysis of the filter membranes. For the first ten weeks, a standard filtering procedure used fibreglass filter papers, which underwent semi-quantitative analysis by XRF. Due to inaccuracies in the filtering procedure and XRF analysis, an improved procedure was devised with quantitative analysis of cellulose nitrate membranes. The most important shortfall of the initial procedure was the failure to detect silicon (Figure

5.2.1), which SEM/EDAX analysis showed to be lost in the initial weeks. Consequently, much of the initial particulate weight loss was not detected by XRF. As the results are cumulative, this altered the appearance of the graph for the sum of elements (Figure 5.2.1). If silicon had been detected the sum of elements occurring as particulate matter may have been closer to -1200 mg m^{-2} at week 10, when the more accurate analysis started. If this was the case the graph for the sum of elements would appear very similar to the graph for total particulate matter (Figure 5.2.1). Slight differences would still have occurred, as XRF does not detect organic matter and as the experiment proceeded, algae was lost from the sandstone.

Considering all the elements monitored using the microcatchment experiment, silicon showed the greatest increase due to the deposition of particulate matter (Figure 5.2.1). The effects of shelter on particulate silicon deposition and the behaviour of soluble silicon will be discussed in Section 5.2.2, as silicon was involved in hydrolysis reactions. Particulate matter, containing aluminium and iron, also accumulated on the sandstone during the microcatchment experiment (Figure 5.2.2). Aluminium was involved in hydrolysis reactions, therefore, further discussion on the effects of shelter and the behaviour of soluble aluminium will be found in Section 5.2.2.

Examination of the results for iron from the exposure trial enables the influence of shelter and location to be considered. Although particulate iron was deposited on to the microcatchments (Figure 5.2.2), a net loss of iron was found for samples in exposed positions (Figure 5.2.3). This suggests that exposed samples were losing iron in solution. Sandstones contain ferrous iron (Fe(II)) as clays, carbonates, sulphides and minor constituents of silicates. Ferric iron (Fe(III)) exists as various oxides. In the case of Hollington Sandstone, the oxide hematite, exists as a fine coating around the grains of the stone. Iron is a relatively insoluble element, but may be lost in solution from sandstone if carbonic acid is present (Keller, 1957). The microcatchment experiment was unsuccessful at monitoring the soluble loss of iron, which was suggested by the exposure trial. This discrepancy may have been due to differences in the way the samples were exposed. The samples used for the exposure trial had a higher surface area to volume ratio (1:5) than the

microcatchment (1:50), possibly increasing dissolution of iron. Also, a difference in the analysis may have contributed to this discrepancy. XRF analysis of the exposure trial samples only detected changes in the surface concentration and it may be that iron was lost only from the surface of the sample or translocated to just below the surface. Samples in sheltered positions (SB and BB) experienced a reduced loss of iron and typically a gain was recorded (Figure 5.2.3). Sheltered samples received less precipitation inputs and therefore, solutional losses can be expected to be lower than for exposed samples. Consequently, gains from particulate deposition may have exceeded losses from dissolution, resulting in an accumulation of iron. Statistically there is strong evidence ($p<0.01$) for this effect of shelter (Table 5.2.2). However, no evidence ($p>0.05$) exists for a difference in the behaviour of iron between samples exposed in Birmingham and those exposed in Preston Montford (Table 5.2.2).

For weathered sandstone collected during the building survey, iron generally showed a slight enrichment (EF Rock > 1) and the amount of enrichment did not vary greatly for different weathering forms (Figure 5.2.4). This slight enrichment seems reasonable as iron was deposited as particulate matter and little may have been lost in solution. The possible dissolution detected by the exposure trial appears less likely to occur for sandstone incorporated into a building. The vertical position of the stones reduces exposure to precipitation and the smaller surface area to volume ratio may reduce dissolution. SEM analysis of the samples from the exposure trial showed that a wide range of atmospheric particles were deposited on to the sandstone, including fly ash and fungal spores which were also noted in previous research (Smith *et al.*, 1994). Cheng *et al.* (1976) found that the type of fossil fuel being burnt, influenced the chemical composition and morphology of the fly ash produced (Table 5.2.3). SEM analysis shows that glassy fly ash from coal combustion (Plate 5.2.1 and Figure 5.2.5) and spongy fly ash particles from oil combustion (Plate 5.2.2 and Figure 5.2.6) were especially common on samples from the exposure trial.

The losses and gains of particulate potassium (Figure 5.2.7) were low in comparison to silicon, aluminium and iron. Initially, potassium was lost as solid particles, but after week fourteen there was an uptake of particulate potassium. Potassium is a major element in fly

ash from coal fired power stations and a minor constituent of fly ash from oil fired stations (Table 5.2.3). Therefore, the fly ash observed by SEM may be an important source of particulate potassium. The effects of shelter on potassium deposition and soluble losses will be discussed in Section 5.2.2 as potassium is involved in hydrolysis reactions.

Particulate matter, containing calcium, magnesium and sodium, accumulated on the sandstone microcatchments over time (Figure 5.2.8). Calcium and magnesium show a very similar pattern of increase and in similar quantities. Both elements are present in fly ash. Sodium shows less of an increase and is not usually reported as a constituent of fly ash (Table 5.2.3). This provides further evidence that fly ash deposition may be major source of particulate matter accumulating on the sandstone. Calcium, magnesium and sodium are all important cations for salt formation and will therefore be discussed in Section 5.2.3.

Particulate matter with a trace of zinc accumulated on the sandstone microcatchments (Figure 5.2.9). Zinc is not a major or minor constituent of fly ash, although enrichment of zinc (EF Rock approximately 400) in weathered sandstone has been reported by Sabbioni and Zappia (1992), who consider refuse incineration as a possible source.

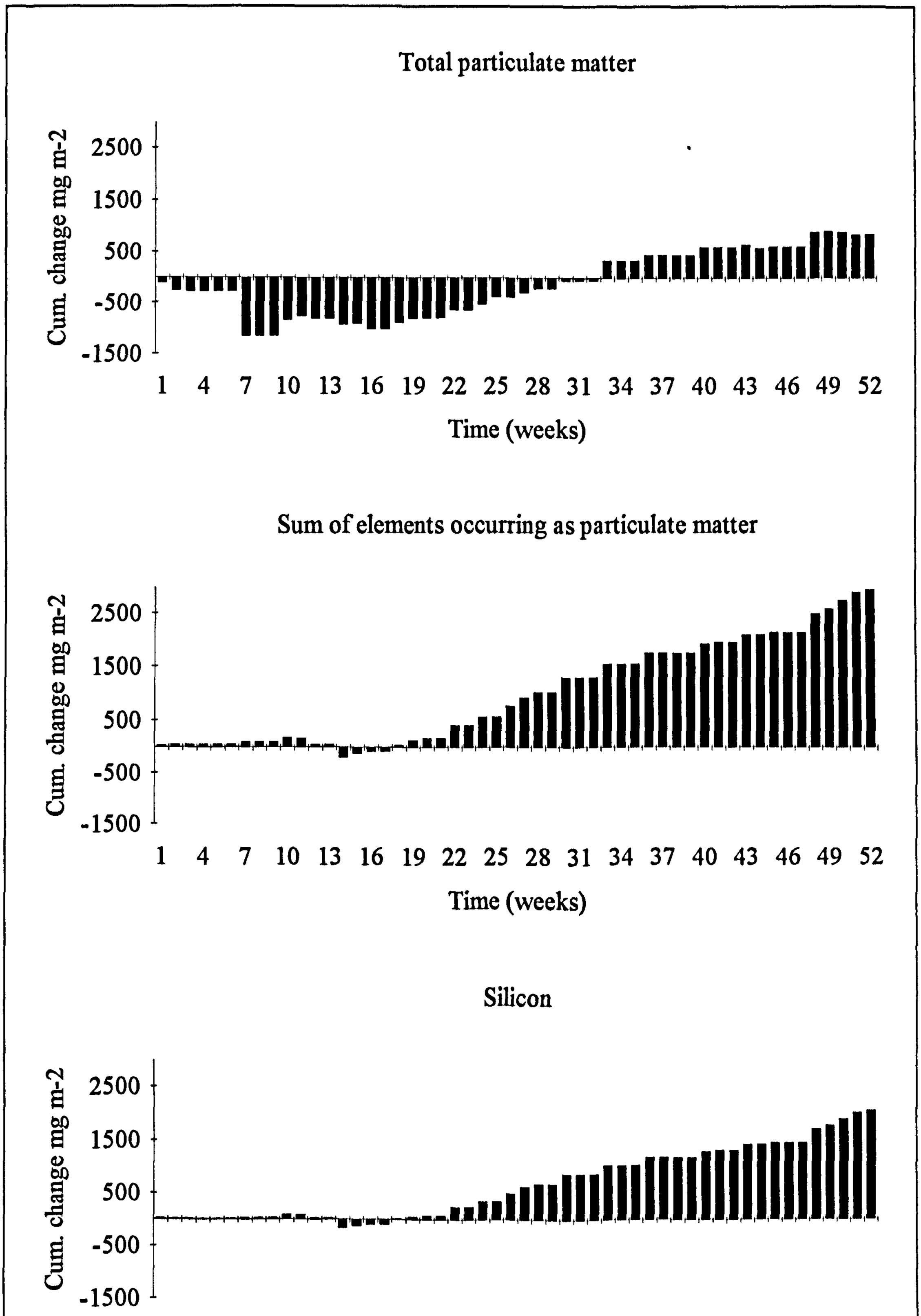

Figure 5.2.1 Cumulative gains and losses (mg m^{-2}) of total particulate matter, the sum of elements occurring as particulate matter and silicon present as particulate matter.

	Exp. time	Weight loss	Particu -lates	Si	K	Ca	Na	Mg	Zn	Fe	SO_4^{2-}	Cl^-	NO_3^-	pH	Temp.
Weight loss	**-0.3562**														
Particulates	-0.2928	***0.9270***													
Si	**-0.4229**	***0.5422***	***0.5257***												
K	***-0.4558***	***0.8672***	***0.7521***	**0.4462**											
Ca	***-0.5334***	***0.8136***	***0.6406***	**0.4354**	***0.8309***										
Na	0.0462	***0.5080***	**0.3679**	0.3310	**0.4082**	0.1823									
Mg	-0.1304	**0.4258**	0.3345	0.1012	0.1831	0.2766	0.0588								
Zn	**-0.1944**	**0.4511**	0.3481	0.1706	0.2094	0.2904	0.1269	***0.9858***							
Fe	0.0901	0.1746	0.2332	-0.0683	0.1245	0.0705	0.0077	-0.0311	-0.0395						
SO_4^{2-}	-0.3425	***0.9269***	***0.8024***	***0.4743***	***0.9448***	***0.8539***	***0.4907***	0.2150	0.2366	0.1908					
Cl^-	-0.0373	***0.5712***	0.3382	0.3326	**0.4421**	***0.4879***	***0.7722***	0.1300	0.1739	-0.1035	***0.5330***				
NO_3^-	**-0.4077**	***0.6058***	***0.4689***	0.1089	***0.5859***	***0.7483***	-0.0529	**0.3978**	**0.3844**	**0.4466**	***0.6275***	0.2033			
pH	***-0.8435***	0.2858	0.2637	**0.4473**	**0.3759**	**0.3911**	-0.0122	0.0176	0.0894	0.0067	0.2795	-0.0023	0.3006		
Temperature	***0.6851***	-0.2016	-0.0712	-0.1046	-0.3213	**-0.4288**	0.0045	-0.1684	-0.2518	0.2216	-0.2018	-0.0994	-0.2768	**-0.3990**	
Volume	-0.0827	***0.7173***	***0.6520***	0.2423	***0.8302***	***0.5536***	**0.4101**	0.1649	0.1770	0.2343	***0.7996***	0.3430	**0.4149**	0.0040	-0.1083

Table 5.2.1 Pearsons correlation matrix for losses from the microcatchment experiment and environmental factors. Figures in bold have some evidence of a correlation ($P<0.05$). Figures in bold italics provide strong evidence of a correlation ($P<0.01$).

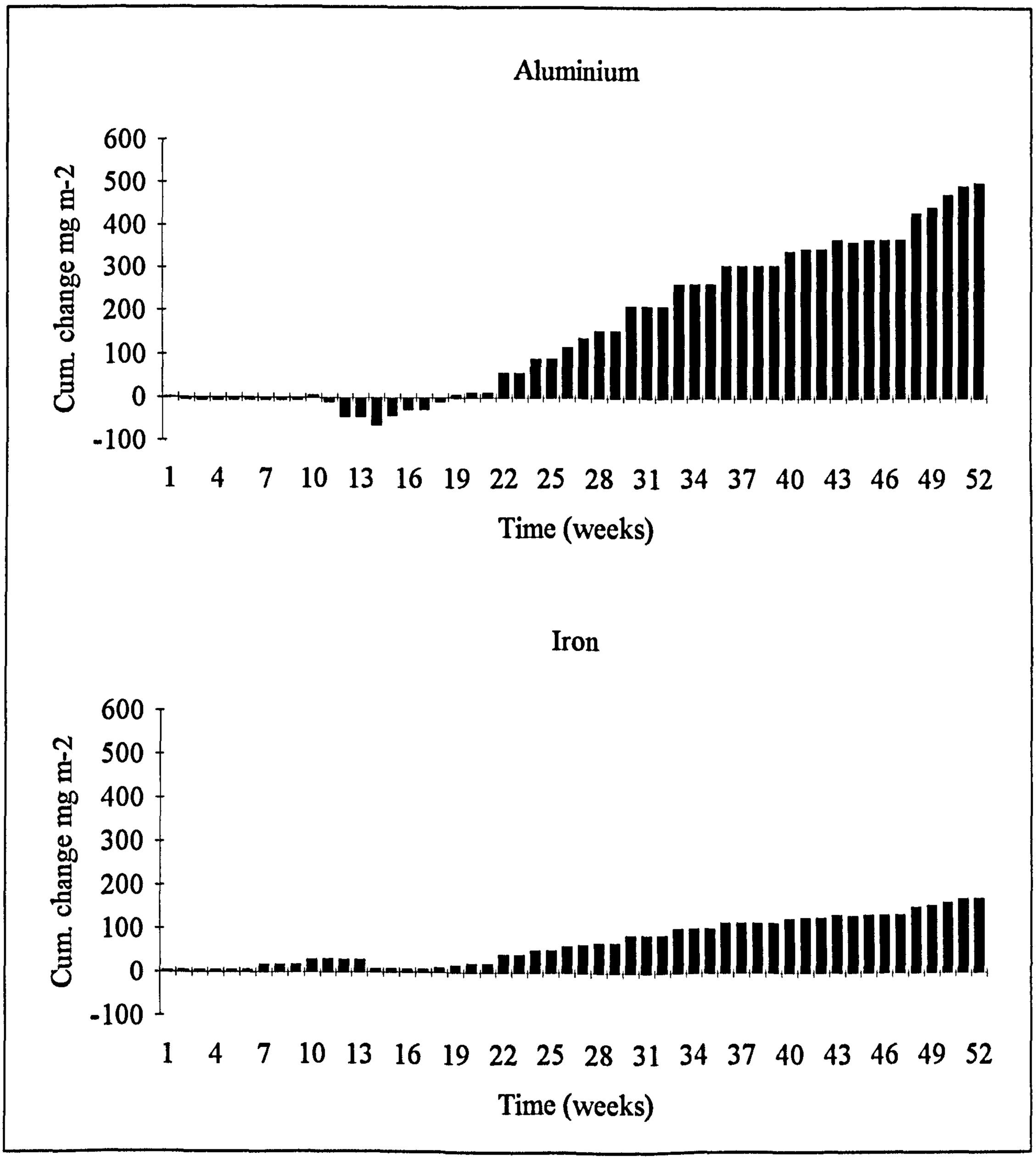

Figure 5.2.2 Cumulative gains and losses (mg m^{-2}) of aluminium and iron present as particulate matter.

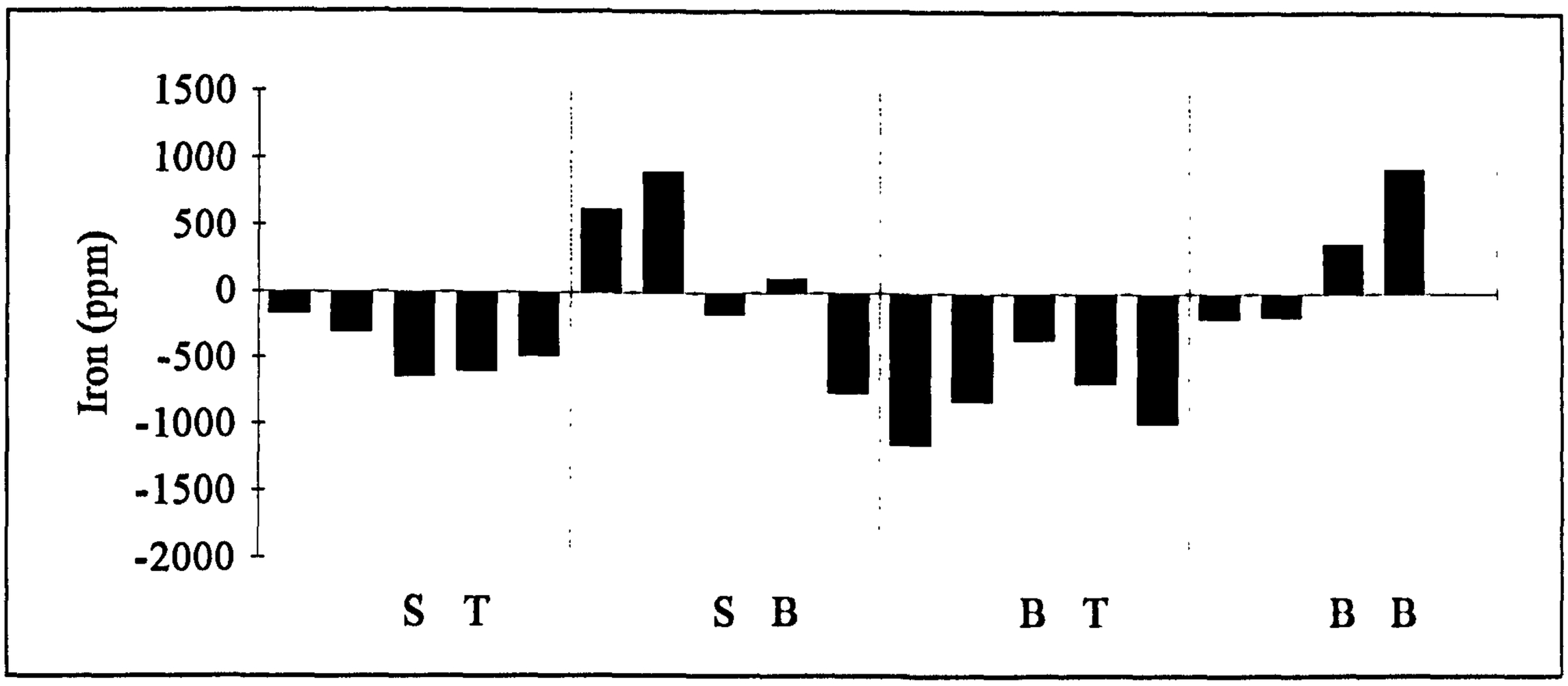

Figure 5.2.3 Changes in the concentration of iron.

ST - Preston Montford top shelf, exposed. SB - Preston Montford bottom shelf, sheltered.

BT - Birmingham top shelf, exposed. BB - Birmingham bottom shelf, sheltered.

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	-448	139	-808	179
Standard Deviation	200	659	305	471
Kurtosis	-1.69	-0.84	0.22	0.50
Skewness	0.54	-0.32	0.60	1.19
Range	470	1670	800	1113
Minimum	-647	-769	-1160	-197
Maximum	-177	900	-360	916
Number of samples	5	5	5	5
Statistical significance of shelter				$p<0.01$
Statistical significance of location				$p>0.05$

Table 5.2.2 Descriptive statistics for changes in iron concentration (ppm).

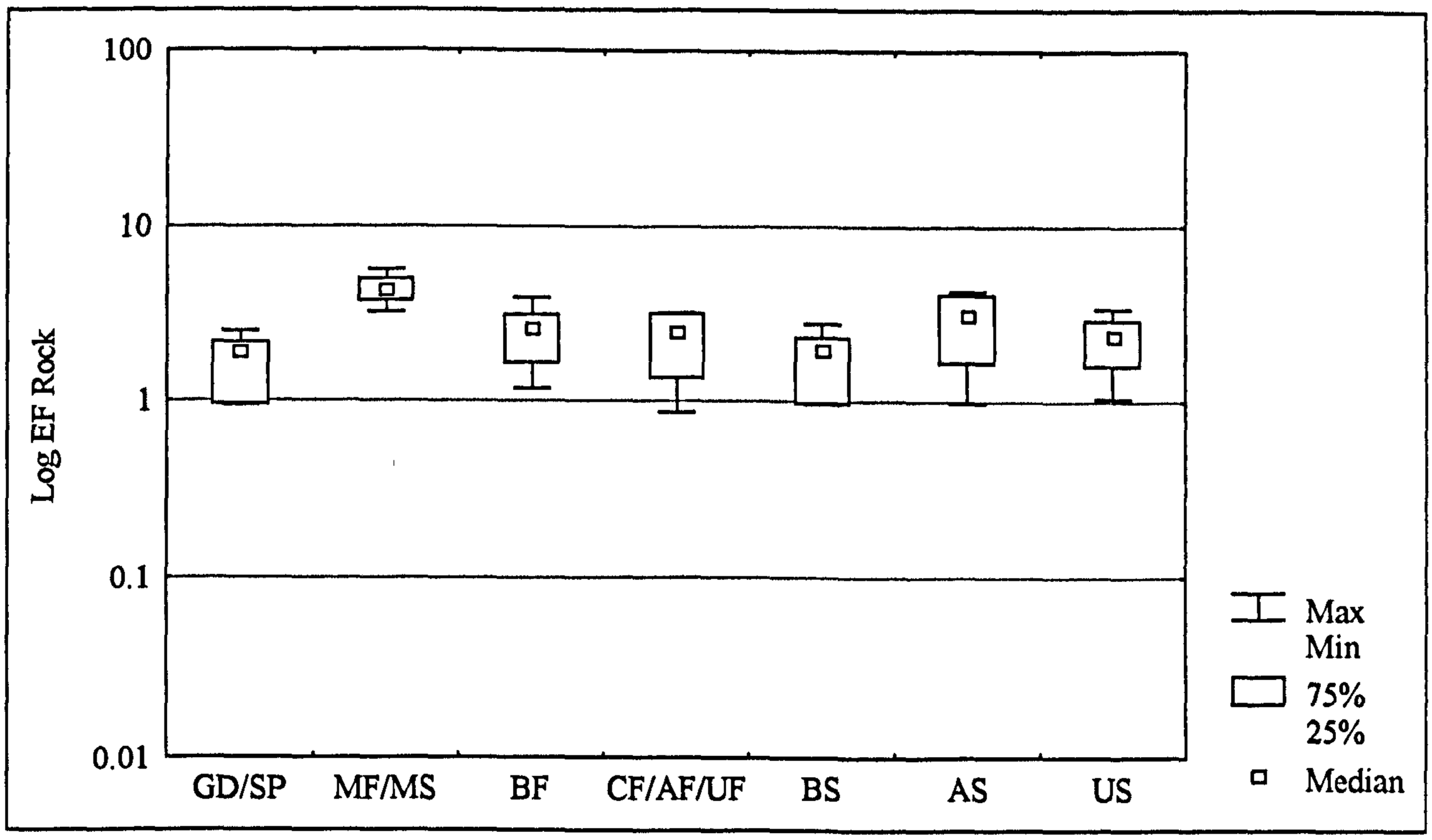

Figure 5.2.4 Enrichment of iron (EF Rock) for sandstones weathered by different forms of weathering (note logarithmic y-axis).

GD-granular disintegration (n=4), SP-spalling (n=1), MF-multiple flaking (n=2), MS-multiple scaling (n=2), BF-black flaking (n=10), CF-case hardened flaking (n=1), AF-autotrophic flaking (n=1), UF-unaltered flaking (n=2), BS-black scaling (n=6), AS-autotrophic scaling (n=4), US-unaltered scaling (n=12).

	Glassy spheres from coal fired boiler	Black spongy spheres from oil fired boiler	White particles from oil fired boiler	Coloured particles from oil fired boiler
Major elements	Si, S, K, Ca, Ti, Fe	Si, S, Ca, V, Fe	Si	S, Fe
Minor elements	Al, P, Cl, Mn, Cu	Mg, Al, P, Ti, Cr, Mn, Ni	Al, S, K, Ca	Ni, V, Mg

Table 5.2.3 Typical elements present as major and minor components of different types of fly ash (after, Cheng *et al.*, 1976).

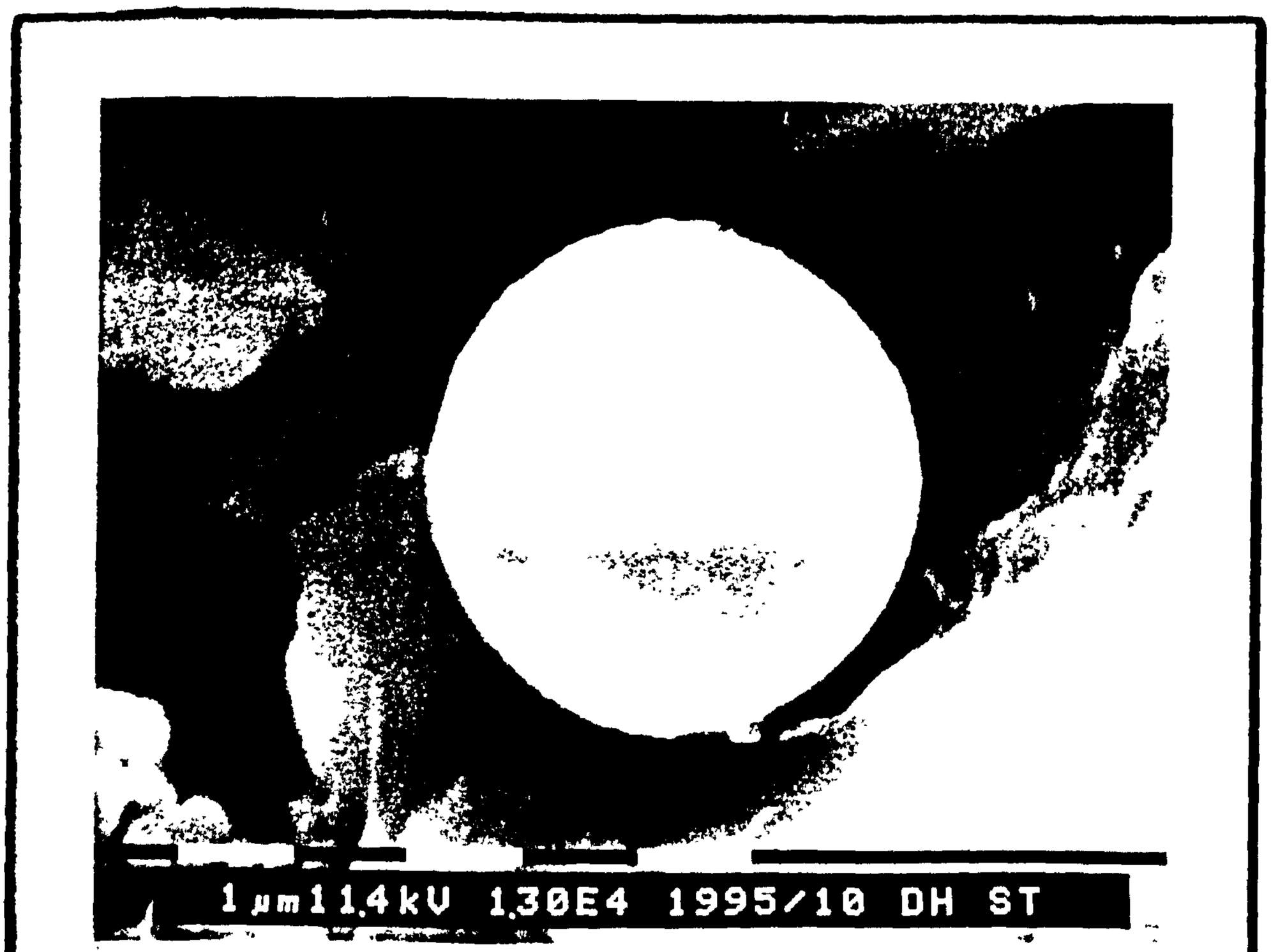

Plate 5.2.1 SEM micrograph of a glassy fly ash particle produced from coal combustion. This sample was in an exposed position for sixteen months in Preston Montford (× 13 000).

Plate 5.2.2 SEM micrograph of a spongy fly ash particle produced from oil combustion. Micro organisms can be seen attached to the particle. This sample was in an exposed position for sixteen months in Birmingham (× 1 550).

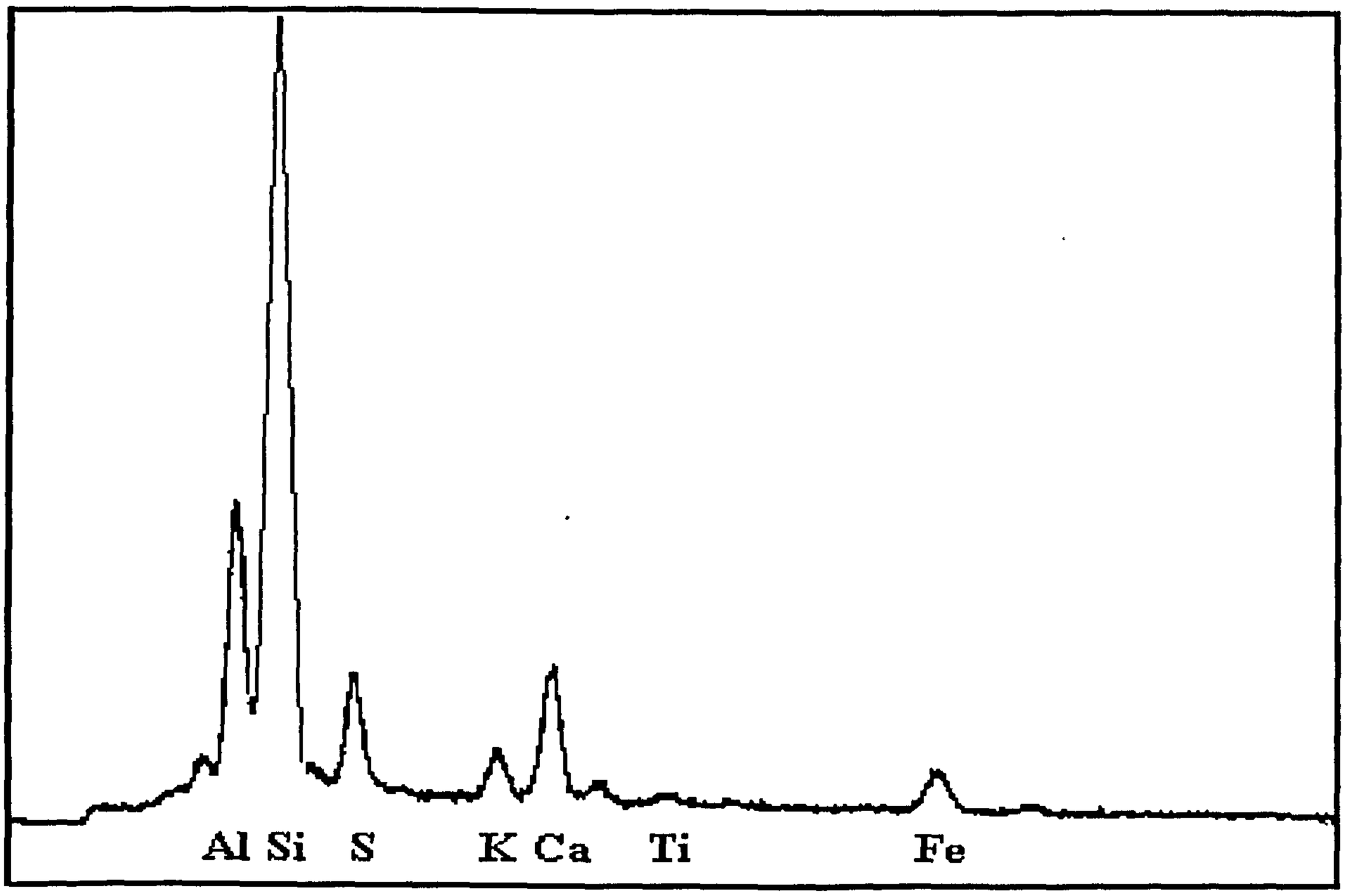

Figure 5.2.5 EDAX spectra for a glassy fly ash particle from coal combustion, deposited on a sample of sandstone from the exposure trial.

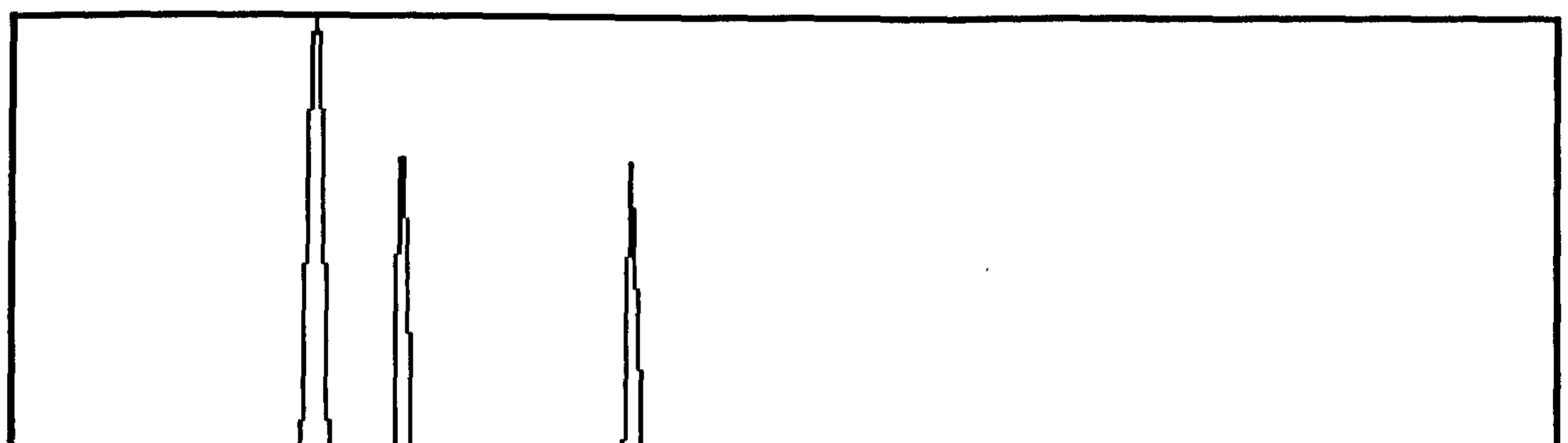

Figure 5.2.6 EDAX spectra for a spongy fly ash particle from oil combustion, deposited on a sample of sandstone from the exposure trial.

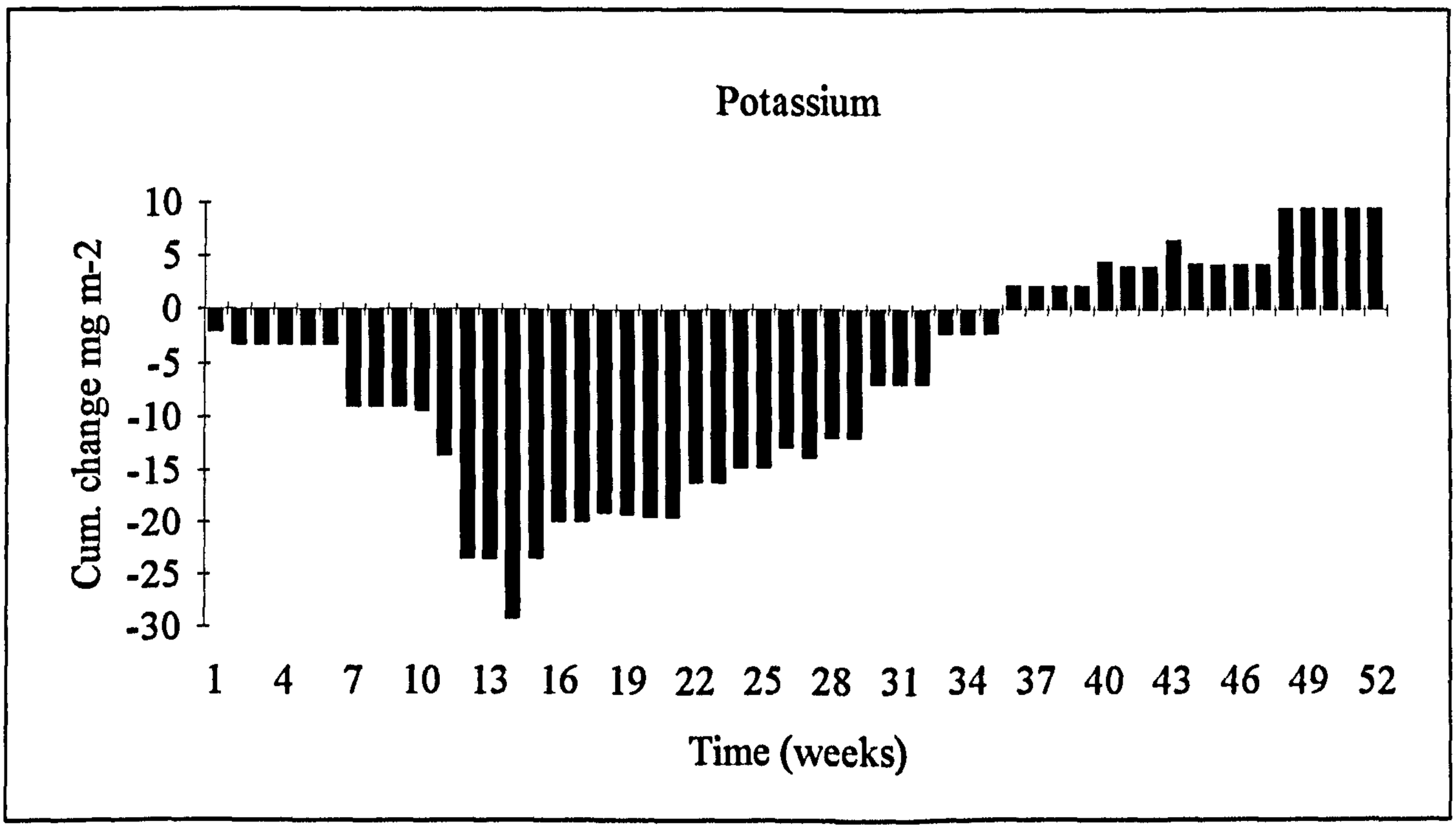

Figure 5.2.7 Cumulative gains and losses (mg m^{-2}) of potassium present as particulate matter.

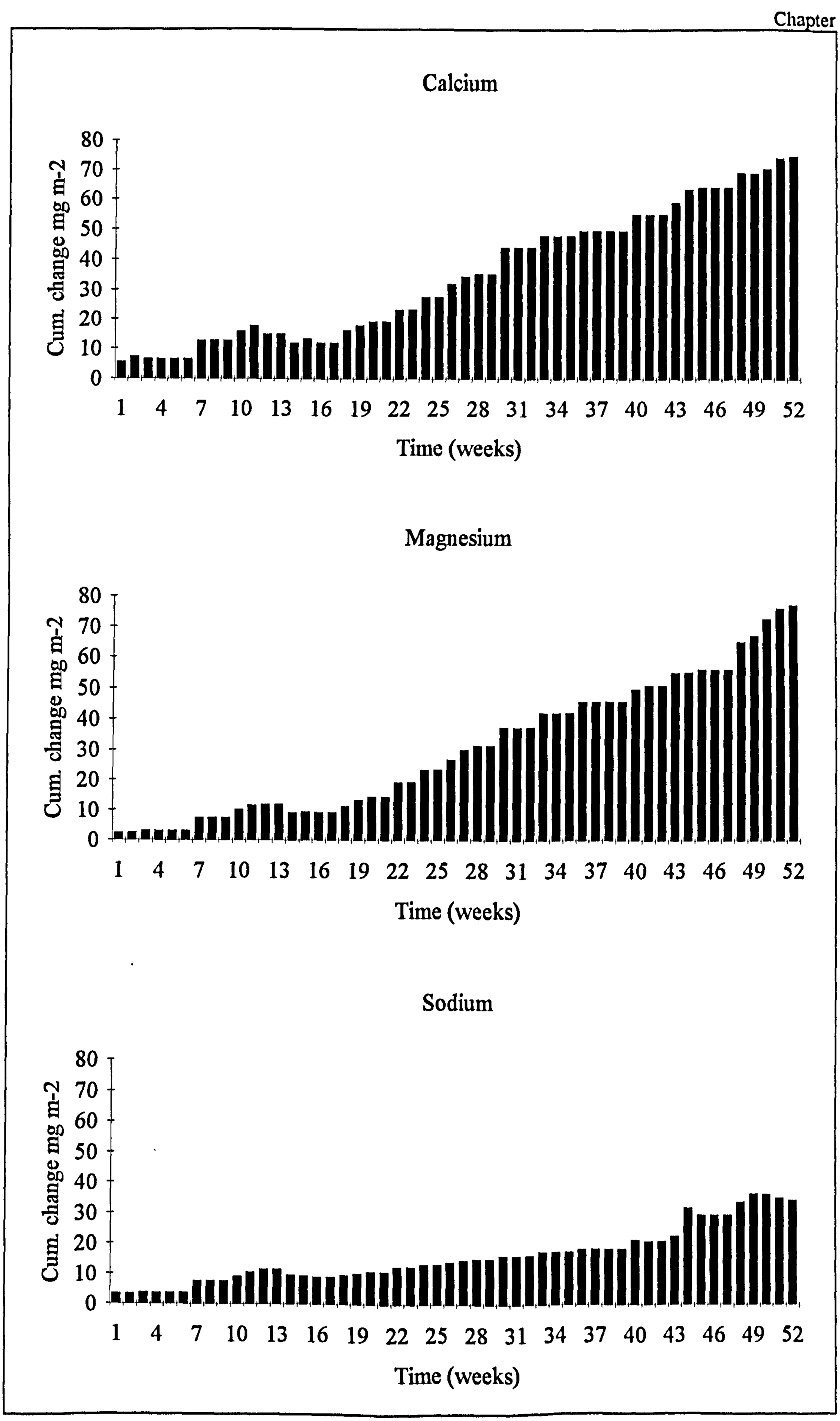

Figure 5.2.8 Cumulative gains (mg m^{-2}) of calcium, magnesium and sodium present as particulate matter.

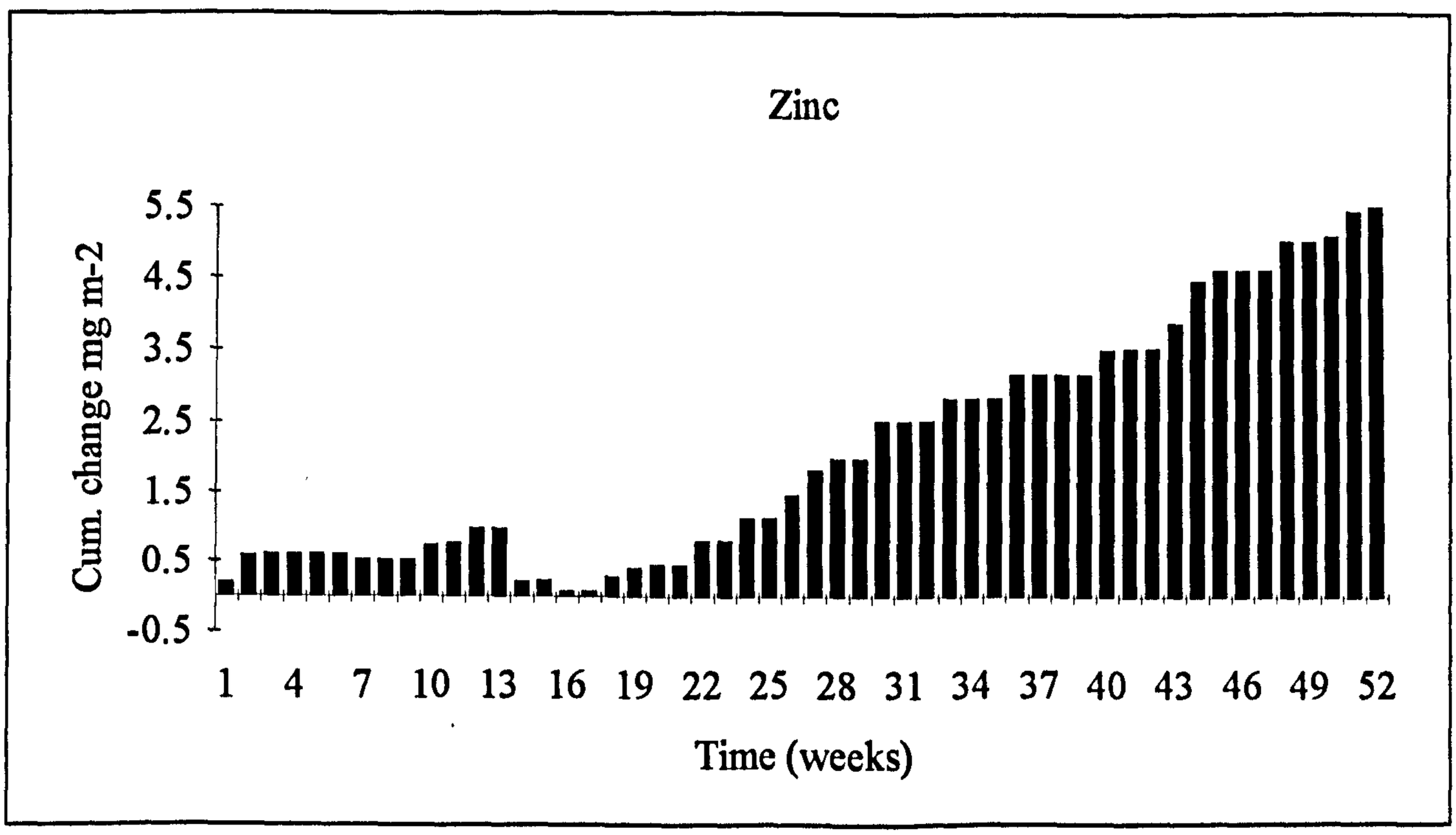

Figure 5.2.9 Cumulative gains (mg m^{-2}) of zinc present as particulate matter.

5.2.2 Hydrolysis Reactions

Hollington Sandstone contains approximately three per cent orthoclase ($KAlSi_3O_8$) which weathers by the process of hydrolysis under acidic conditions, to leave kaolinite [$Al_4Si_4O_{10}(OH)_8$] (Velde, 1992). Evidence for the hydrolysis of orthoclase contained in the sandstone is provided by the statistically significant ($p<0.05$) loss of potassium found with the microcatchment experiment (Figure 5.2.10). The process of hydrolysis is dependent on water to supply hydrogen ions (Equation 5.2.1). This dependence on water is demonstrated by a Pearsons correlation coefficient of 0.83 between potassium loss and weekly runoff volume (Table 5.2.1).

$$4KAlSi_3O_8 + 8H^+ \rightarrow Al_4Si_4O_{10}(OH)_8 + 4K^+ + 8Si^+ + 14O^{2-}$$

Equation 5.2.1

Results from the exposure trial also demonstrate the importance of water availability, with potassium lost from exposed positions, but not sheltered ones (Figure 5.2.11). There is strong statistical evidence ($p<0.01$) for this influence of shelter (Table 5.2.4). Samples in sheltered positions actually gained potassium, possibly due to the deposition of particulate matter, as detected by the microcatchment experiment (Section 5.2.1). No evidence ($p>0.05$) exists for an influence of location (Table 5.2.4).

The formation of kaolinite does not cause disruptive pressure in the stone as it is a non-swelling clay. However, the clay mineral formed is dependent on pH, with sandstones containing little calcareous material typically experiencing acidic hydrolysis. However, calcareous sandstones or non calcareous stones with an external source of calcium will experience a higher pH and under these conditions smectite may form. As smectite is a swelling clay, expansion and contraction due to wetting-drying cycles, may cause deterioration.

Although results show that kaolinite is the dominant clay formed in this study, some deterioration may result from it's formation. Sramek (1992) has found that a one percent increase in kaolinite content causes approximately a 10 N mm^{-2} reduction in the

compressive strength of the stone. Furthermore, the porosity of the stone increases and a general reduction in durability is found (Sramek, 1992). The author failed to consider rates of kaolinite formation due to hydrolysis reactions, however using the estimate of 10 N mm^{-2} and details from the microcatchment experiment, this procedure can be completed. The procedure requires the assumptions that potassium loss from the microcatchments is a good indicator of the rate of kaolinite formation, formation of kaolinite is linear over time, and that Sramek's estimate is valid. This procedure suggests a reduction in compressive strength of Hollington Sandstone by 1 N mm^{-2} in around 60 years (Appendix 6). This figure is not precise and only provides an indication of the role orthoclase hydrolysis may have in sandstone deterioration. However, this figure is a more accurate assessment than 1 N mm^{-2} in around 45 years provided by Halsey *et al.* (1995) as it is based on a larger data set. As the sandstone has a compressive strength of around 32 N mm^{-2} (O'Neil, 1965), significant weakening will take a considerable time.

Orthoclase hydrolysis also causes the release of silicon ions (Equation 5.2.1), which in the pH ranges suggested by the microcatchment experiment (Figure 5.2.12) will be soluble (Figure 5.2.13). Indeed, a statistically significant ($p<0.05$) loss of silicon was experienced by the microcatchments (Figure 5.2.10). Therefore, it would be reasonable to expect a loss of silicon for the exposure trial samples in exposed positions. This was not the case and there was actually a gain of silicon for most exposed samples and generally a loss for sheltered samples (Figure 5.2.11 and Table 5.2.5). It must be remembered that the results for the exposure trial are not absolute elemental changes. A change in the concentration of one element is relative to changes in other elements. For example, if an element remained stable a dilution effect may have been exerted on to it due to a gain of other elements. Conversely, a concentration effect may have occurred for a stable element due to the loss of other elements. An alternative to calculating relative elemental changes was to use a stable element, such as titanium, to calculate absolute elemental changes. However, this was found inappropriate in this experiment (Section 5.3).

Silica (SiO_2) makes up 85 per cent of Hollington Sandstone. The largest loss of silica was 7.5 per cent which is about 9 per cent of the total silica concentration. Such large losses of

silica appear unlikely, therefore it seems that much of the apparent silica loss was due to the dilution effect discussed above. To demonstrate this dilution effect, changes in silicon concentration have been correlated with those for calcium and sulphur, which were the two major elements increasing in concentration in the sheltered samples (Figure 5.2.14). The Pearsons correlation coefficients (Table 5.2.6) show that there are strong negative correlations between these elements and silicon, for samples in sheltered positions. These negative correlations indicate that the silicon concentration decreased as calcium and sulphur increased. The most likely reason for this is the dilution effect, explained above. Correlation coefficients are closer to zero for samples in exposed positions, suggesting that silicon was less stable in exposed positions. Indeed, the microcatchment experiment did detect the dissolution of silicon in an exposed position.

Aluminium occurs in sandstones chiefly as aluminosilicates, such as, feldspars, micas and clays (Pettijohn *et al.*, 1972). The microcatchment experiment failed to detect the dissolution of aluminium due to aluminium being below the limits of detection of ICP. However, due to this, aluminium was only analysed in the first three months of the microcatchment experiment and not for the remainder of the time. Alumina (Al_2O_3) dissolution is strongly dependent on the pH of the available water; below pH 4.5 and above pH 8 alumina is highly soluble, while between these values dissolution is negligible (Figure 5.2.13). The pH of runoff water from the sandstone microcatchment experiment can be used as a guide to the pH of the water contained in the sandstones pores (Figure 5.2.12). The pH of the runoff decreased over time (due to the loss of base cations) and a pH below 4.5 was not uncommon at the end of the study period, hence allowing dissolution of alumina and a loss of aluminium. Therefore, it is not surprising that aluminium was below the limits of detection during the initial stages of the experiment. However, had it been analysed after week 43 ($pH<4.5$) a loss of aluminium may have been detected.

A change in aluminium concentration was found for all groups of samples from the exposure trial (Figure 5.2.11), however, there is no statistical evidence ($p>0.05$) for a difference between samples exposed in Birmingham and those exposed in rural Preston Montford (Table 5.2.7). Strong evidence ($p<0.01$) exists for an influence of shelter, with

samples in exposed positions showing a consistent loss, whereas those in sheltered positions show a reduced loss and typically a gain of aluminium (Figure 5.2.11).

The mechanism responsible for the loss of aluminium in exposed positions is not clear. It may simply have been due to dissolution in the surface layer of the stone, in a similar manner discussed for iron in Section 5.2.1. Significant losses of alumina have been reported for weathered basalt and andesite, and although no conclusive evidence exists, chelation was suggested as a possible mechanism (Colman, 1982). Chelation involves the holding of an ion, usually a metal, in a compound of organic origin with a ring molecular structure. Plants use chelation to extract ions in environments where they would normally be precipitated. In this study chelation may have contributed to the loss of aluminium, as SEM revealed the presence of algal and fungal growth on many samples (Plate 5.2.3). Deposition of particulate matter containing aluminium was observed with the microcatchment experiment, however the gain in aluminium from this mechanism was exceeded by dissolution, to give an overall loss of aluminium for samples in exposed positions.

The lower loss of aluminium found for some of the sheltered samples may be due to reduced inputs of water, limiting dissolution or chelation (Figure 5.2.11). However, many of the sheltered samples demonstrated a gain of aluminium and this may have been due to the deposition of particulate matter, such as fly ash, which may contain aluminium (Section 5.2.1). Deposition of aluminium was found to be greater on the sheltered samples exposed in Birmingham, than sheltered samples in Preston Montford (Table 5.2.7). This may have been due to higher concentrations of particulates occurring in Birmingham than in Preston Montford, however this finding was not statistically significant.

Analysis of weathered sandstone shows that potassium, silicon and aluminium are enriched slightly for all weathering forms (Figure 5.2.14). Little difference occurs in the EF Rocks for different weathering forms. This enrichment may be due to gains from particulate matter deposition, exceeding solutional losses. Alternatively, dissolution of silicon, aluminium and potassium from the subsurface of the stone, which then precipitates at the surface of the stone may be responsible. Therefore, the weathering of vertically positioned stones on buildings is more similar to the exposure trial samples in sheltered positions, than those in exposed positions.

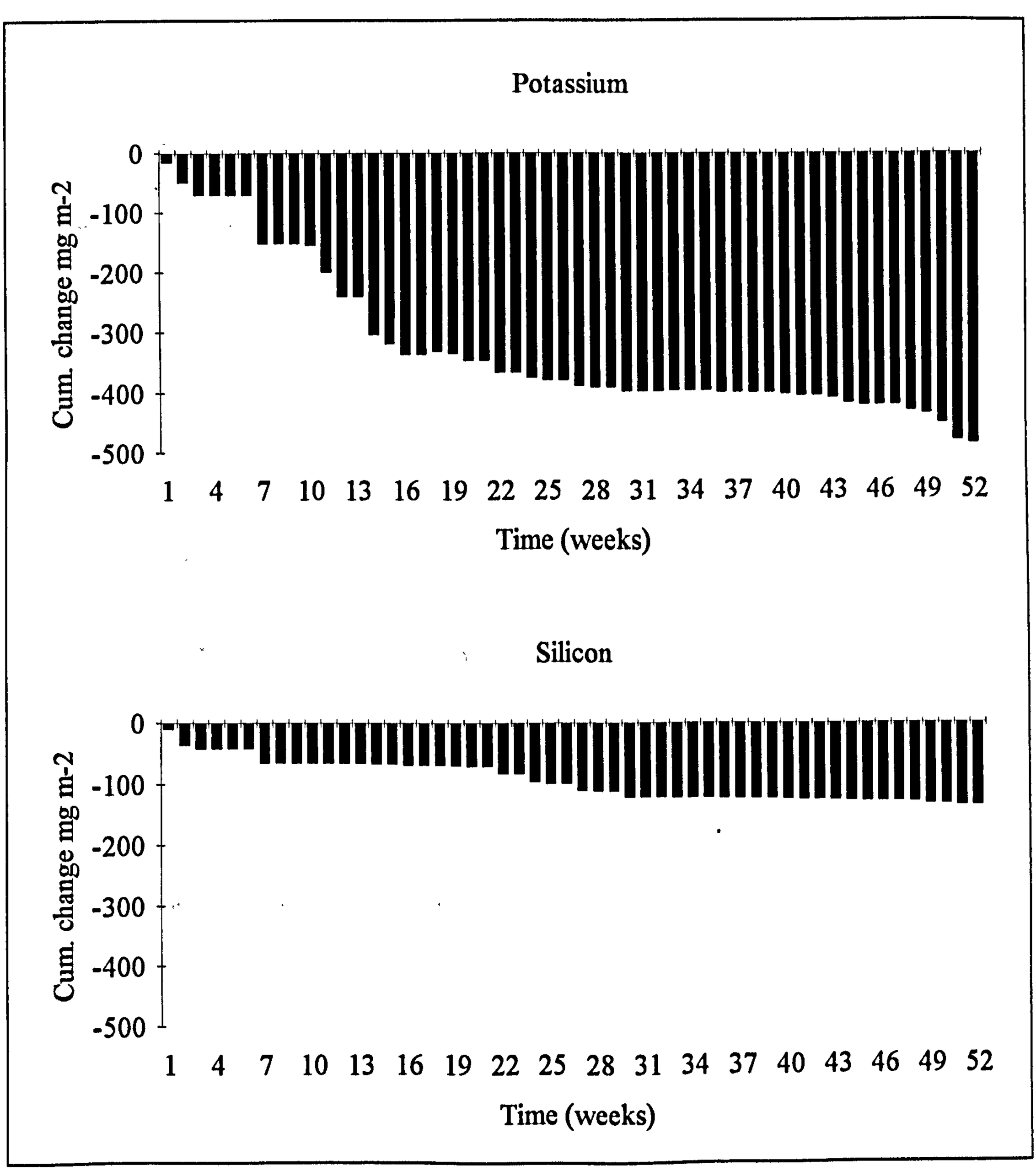

Figure 5.2.10 Cumulative losses (mg m^{-2}) of soluble potassium and silicon.

Plate 5.2.3 SEM micrograph of micro organisms growing on a sample exposed on the top shelf of the Birmingham rack for sixteen months. Micro organisms can be seen penetrating into a quartz crystal (× 1 550).

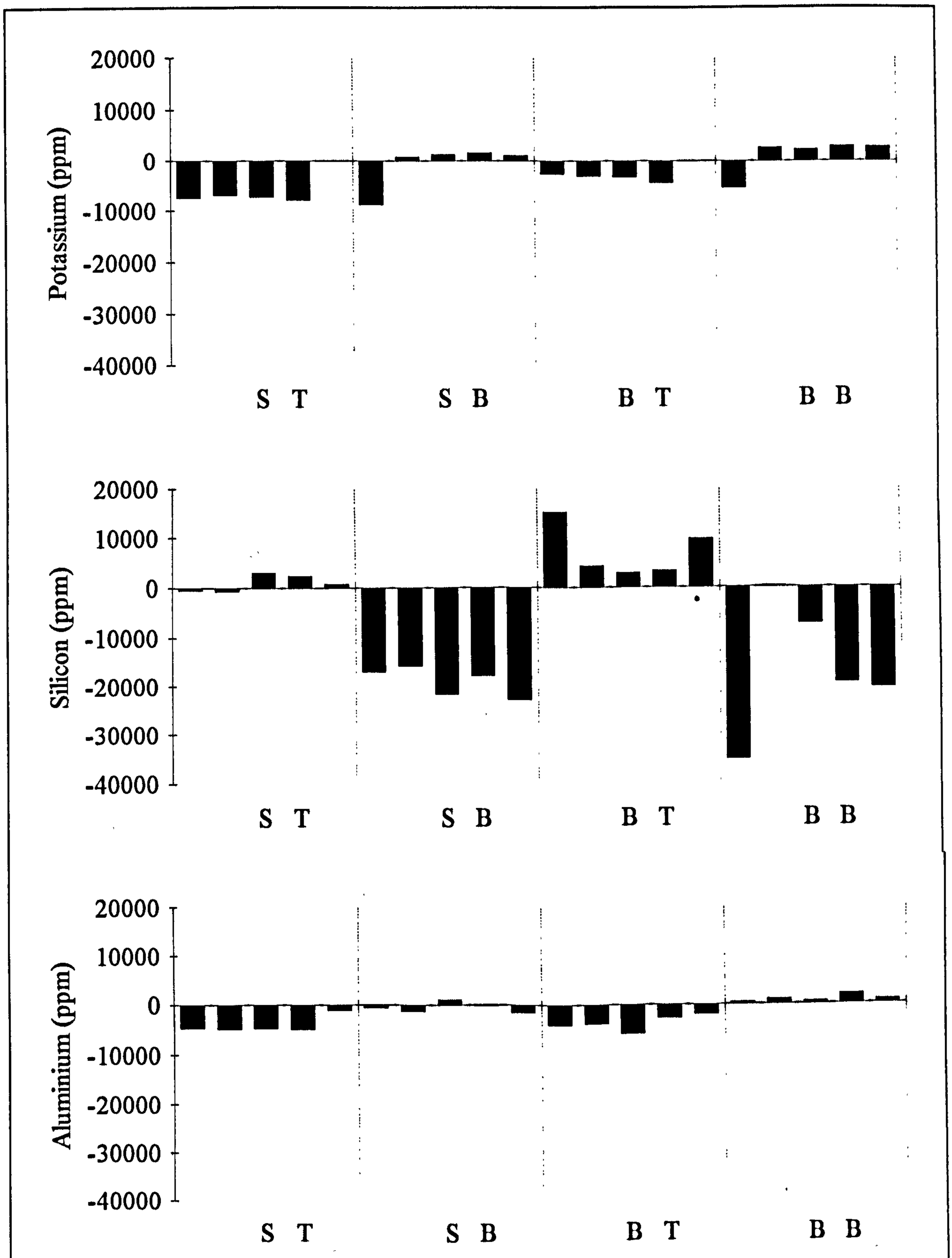

Figure 5.2.11 Changes in the concentration of potassium, silicon and aluminium.

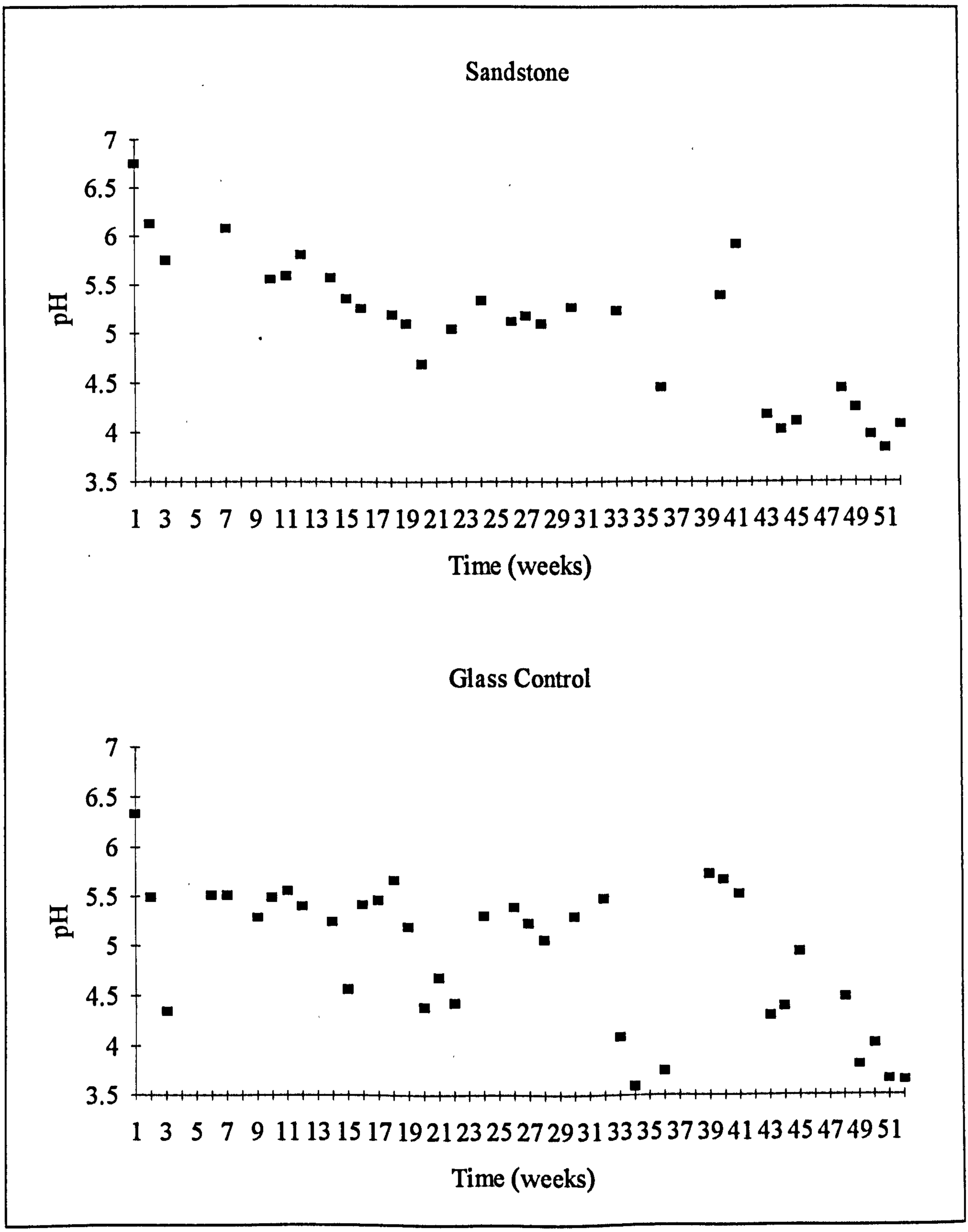

Figure 5.2.12 pH of runoff water from sandstone and glass control microcatchments.

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	-7730	1162	-3812	2573
Standard Deviation	739	298	1076	224
Kurtosis	1.33	0.70	-0.67	0.69
Skewness	-1.09	0.77	-0.86	-0.79
Range	1942	792	2639	589
Minimum	-8894	820	-5392	2234
Maximum	-6951	1612	-2752	2822
Number of samples	5	5	5	5
Statistical significance of shelter				$p<0.01$
Statistical significance of location				$p>0.05$

Table 5.2.4 Descriptive statistics for changes in potassium concentration (ppm).

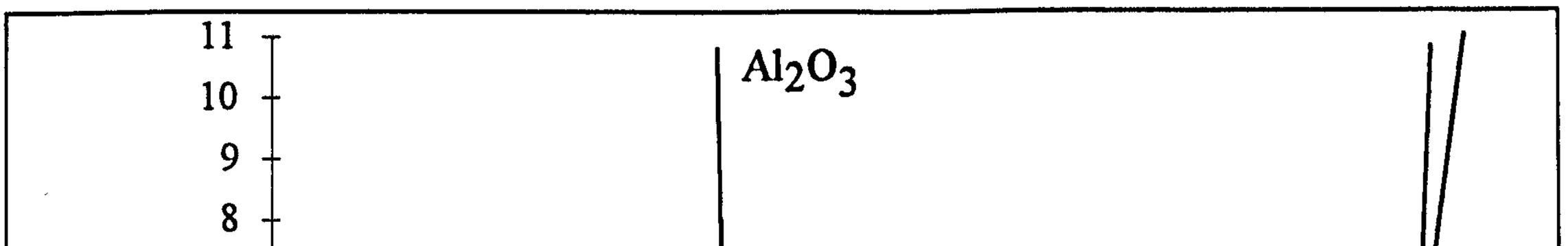

Figure 5.2.13 The solubility of silica and alumina as a function of pH (after Keller, 1957).

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	883	-18976	7050	-16353
Standard Deviation	1666	3047	5319	13455
Kurtosis	-2.61	-2.42	-0.26	-0.26
Skewness	0.25	-0.43	1.11	-0.27
Range	3726	7059	12347	35160
Minimum	-833	-22779	2807	-35120
Maximum	2893	-15720	15154	40
Number of samples	5	5	5	5
Statistical significance of shelter				p<0.01
Statistical significance of location				p>0.05

Table 5.2.5 Descriptive statistics for changes in silicon concentration (ppm).

Sample group	Correlation coefficients		
	Ca	S	Ca + S
ST	0.248	-0.356	-0.314
SB	-0.986	-0.940	-0.961
BT	0.478	-0.924	-0.940
BB	-0.971	-0.962	-0.968
All	-0.806	-0.858	-0.851

Table 5.2.6 Pearsons correlation coefficients between silicon and calcium, silicon and sulphur, and silicon and the sum of calcium and sulphur.

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	-4135	-592	-3803	805
Standard Deviation	1600	1056	1470	648
Kurtosis	4.92	0.43	0.47	1.85
Skewness	2.21	0.90	-0.57	1.37
Range	3719	2677	3893	1617
Minimum	-4998	-1658	-5970	244
Maximum	-1278	1019	-2077	1861
Number of samples	5	5	5	5
Statistical significance of shelter				p<0.01
Statistical significance of location				p>0.05

Table 5.2.7 Descriptive statistics for changes in aluminium concentration (ppm).

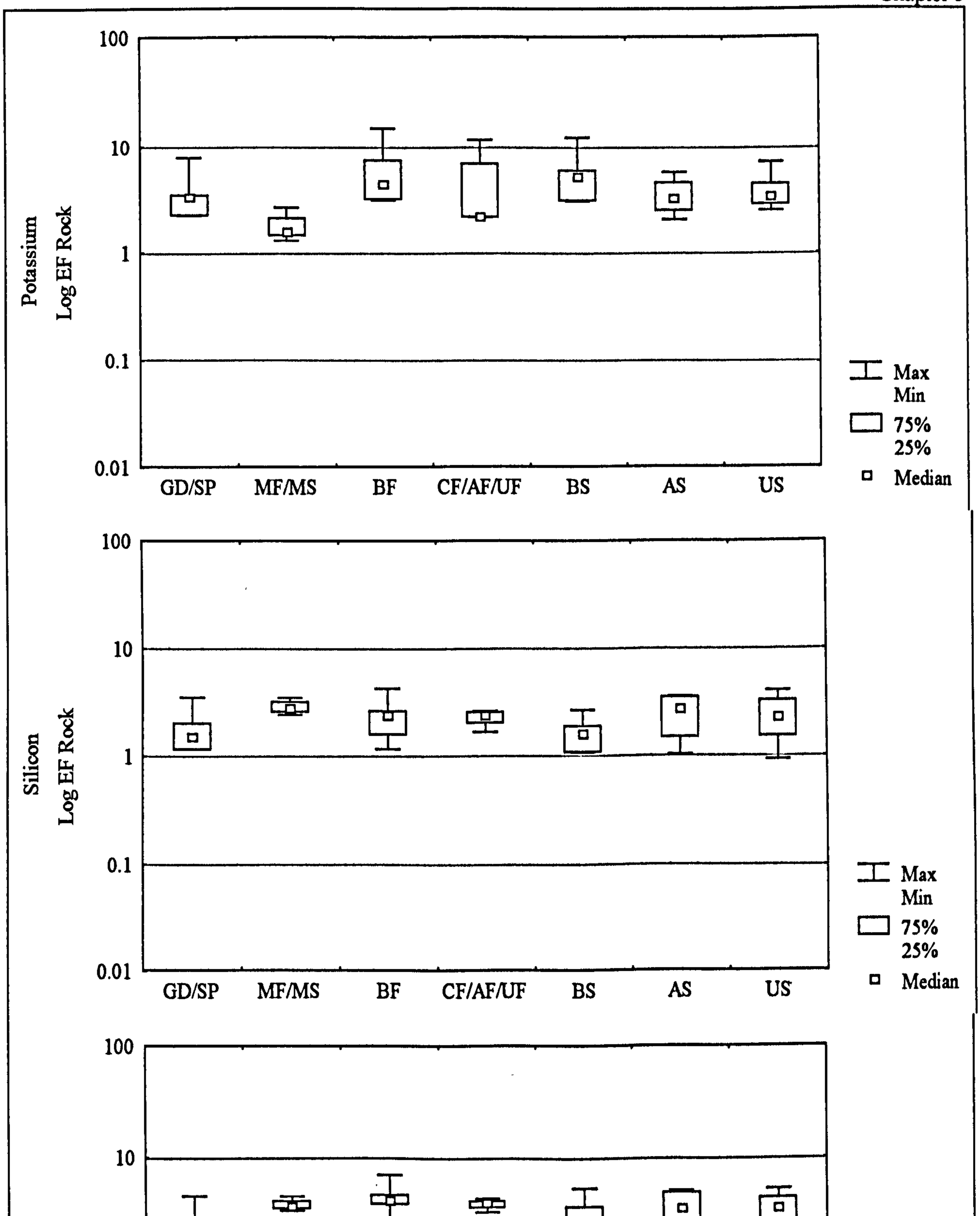

Figure 5.2.14 Enrichment (EF Rock) of potassium, silicon and aluminium for sandstones weathered by different forms of weathering (note logarithmic y-axis).

5.2.3 Formation of Soluble Salts

The patterns of calcium and sulphate losses from the microcatchment experiment were very similar, suggesting that the two elements were combining to form the salt gypsum ($CaSO_4.2H_2O$) or possibly anhydrite ($CaSO_4$) (Figure 5.2.15). Paired t-tests show that this loss was highly significant ($p<0.01$) for both calcium and sulphate. Gypsum is an extremely common salt found in deteriorated stone work and it affects many different types of stone. Formation of gypsum is often attributed to the sulphation of calcium, contained within the stone or derived from the mortar surrounding the stone, with atmospheric sulphur oxides (SO_X). In the case of Hollington Sandstone the calcium content is extremely low, about 0.06% (expressed as CaO) (Table 5.1.1). Although this appears low, it provides approximately 40 000 mg of calcium in a metre square slab of Hollington Sandstone. This is sufficient to account for the calcium lost during the microcatchment experiment, but it is possible that the atmospheric deposition of calcium, discussed in Section 5.2.1, was increasing the rate of gypsum formation. Dry deposition of calcium on to an almost pure silicate sandstone has previously been quoted as a mechanism responsible for gypsum formation (Steiger *et al.*, 1993). However, Steiger *et al.* (1993) failed to state the calcium content of the stone and this is essential to assess the importance of atmospheric calcium, upon gypsum formation.

Once gypsum has formed in the stone it remains until the next rainfall event, when it is taken into solution. Where rainfall is great enough to form runoff, the gypsum may be lost. However, when runoff does not occur, the gypsum recrystallizes as the sandstone dries out. The role of runoff, washing gypsum from sandstone, is shown by Pearsons correlation coefficients between sulphate loss and weekly runoff volume, and calcium loss and weekly runoff volume, with coefficients of 0.80 and 0.55, respectively (Table 5.2.1).

The results for calcium and sulphur from the exposure trial agree well with those from the microcatchment experiment. Calcium and sulphur show a similar pattern of changes, especially for samples in sheltered locations (Figure 5.2.16). Typically both elements show a loss in exposed positions, but accumulate in sheltered positions (Figure 5.2.16). This effect of shelter is statistically significant for calcium ($p<0.05$) (Table 5.2.8) and sulphur

($p<0.01$) (Table 5.2.9). The calcium and sulphur increases for sheltered samples may have occurred due to the deposition of calcium contained in particulate matter, possibly fly ash (Section 5.2.1). The same mechanism may have been involved in the increase in sulphur concentration, but unfortunately the gain of particulate sulphur could not be analysed with XRF. Indeed, Smith *et al.* (1992) suggests particulate gypsum may be deposited on to stone. This view is supported by the strong correlation between calcium and sulphur gain in sheltered locations (Table 5.2.10).

Analysis of weathered sandstone from buildings shows that it is generally enriched in calcium and sulphur (Figure 5.2.17). The enrichment (EF Rock) of calcium and sulphur both show a similar pattern for different weathering forms. However, the enrichment of calcium (mean EF Rock of 15) is not as marked as that of sulphur (mean EF Rock of 275) and in a few cases there is a loss of calcium (Figure 5.2.17) and (Table 5.2.12).

The concentration of soluble sulphate and soluble calcium in weathered stone shows a very similar pattern to the EF Rocks (Figure 5.2.18). Again sulphate is enriched to a greater degree than calcium (Table 5.2.11). There is an apparent influence of weathering form upon the soluble contents and EF Rocks for calcium and sulphur. Stones weathered by flaking (CF/AF/UF and BF) have the highest enrichment of calcium and sulphur, especially black flaking. After flaking, scaling stone (BS, AS and US) have the highest enrichment of calcium and sulphur, especially black scaling. It is difficult to distinguish if these higher enrichments cause the weathering forms or they are an effect of them. It may seem reasonable that an enrichment of gypsum promotes flaking and scaling due to cycles of crystallisation and hydration. The higher enrichment found for flaking than for scaling stone may be an affect of the weathering forms. Flakes are thinner than scales and as calcium and sulphur enrichment may be greater at the surface, the enrichment may be greater for flaking than for scaling. It must also be observed that there is great variability in the EF Rocks for each weathering form. In some cases there is a loss of calcium (EF Rock <1). The exposure trial and the microcatchment experiment found that exposure to rainfall was very important in causing the loss of calcium and sulphur from the stone. It may be this factor that causes the variability in EF Rocks and the soluble content of calcium and sulphur.

If gypsum builds up in the pores of the sandstone, it can exert pressure by changes in volume, either due to a change in hydration state, cycles of dissolution and re-crystallisation or differential thermal expansion. Analysis of the data for calcium and sulphate losses from the microcatchment experiment gives a mean molecular ratio of 2.05. This indicates that not all the calcium is lost from the stone as gypsum. The majority of calcium contained in sandstones occurs as carbonate, either in calcite or dolomite (Pettijohn, 1972). Previous research on sandstones found this extra calcium to be lost due to the direct dissolution of calcite (Steiger *et al.*, 1993). Calcite and dolomite occur as cementing agents in sandstones and their dissolution may in time cause weakening in areas of the stone experiencing dissolution.

Sodium and chloride show an irregular, but similar pattern of losses and gains for the first 31 weeks of the microcatchment experiment, suggesting that the two elements may have combined to form the soluble salt halite (NaCl) (Figure 5.2.19). The presence of halite during this period is supported by a mean sodium to chloride molecular ratio of 1.02. The exact mechanism of halite formation is not clear, but it may be derived from marine aerosols (Smith *et al.*, 1992). Paired t-tests show the difference between the sandstone and the glass microcatchments is not significant ($p>0.05$) for sodium, but it is significant ($p<0.05$) for chloride.

The exposure trial failed to monitor a change in the concentration of sodium and chloride and therefore no information is available on the effects of shelter or location. Analysis of weathered sandstone generally shows an enrichment (EF Rock >1) for both sodium and chloride (Figure 5.2.20). The mean EF Rocks for sodium are very high for black flaking and black scaling compared to other weathering forms (Table 5.2.12). Generally, the mean EF Rocks for chloride are not as high as those for sodium and the EF Rocks for black flaking and black scaling are only slightly higher than for other weathering forms. In fact very little relationship exists between the enrichment of sodium and chloride.

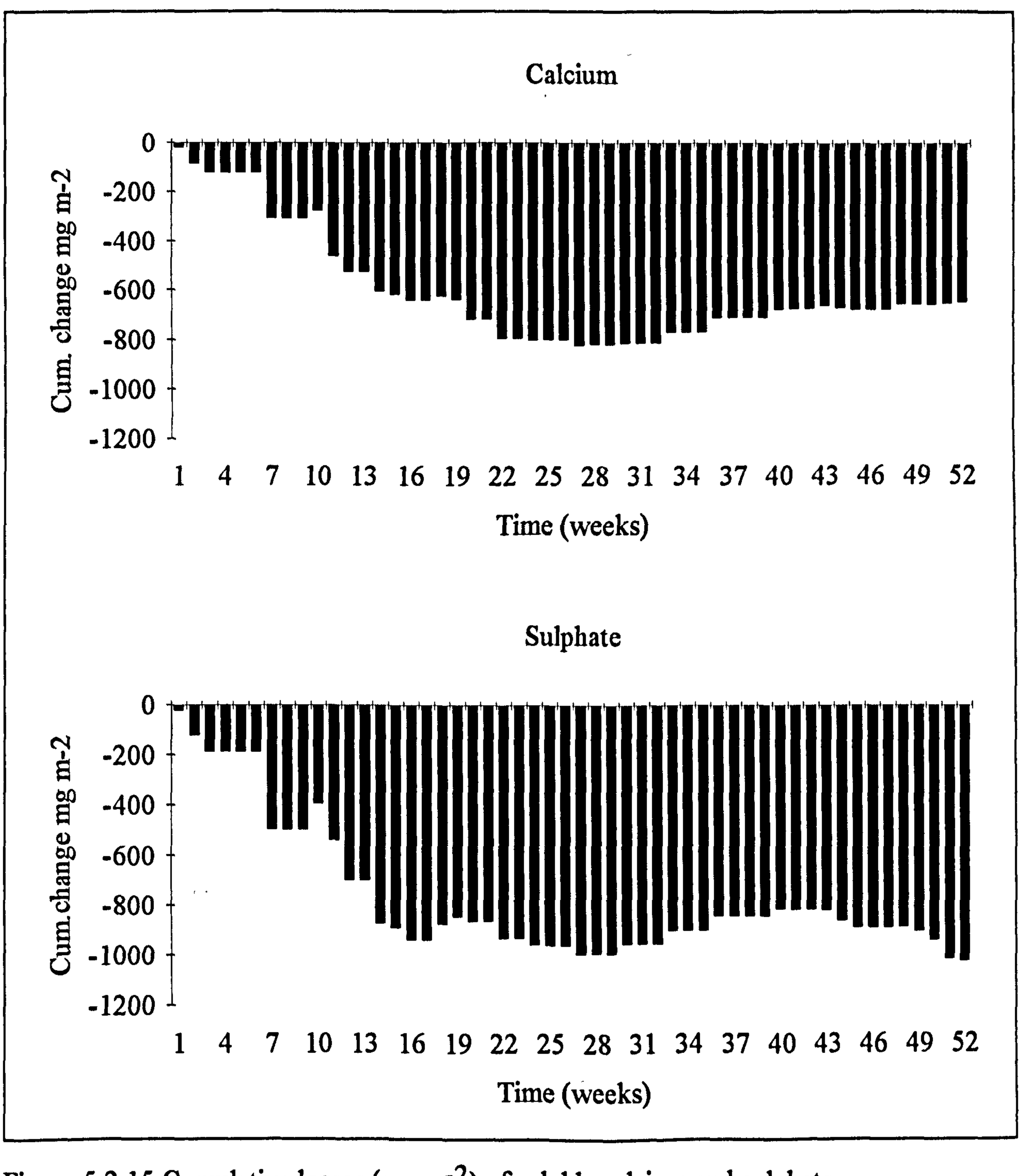

Figure 5.2.15 Cumulative losses (mg m^{-2}) of soluble calcium and sulphate.

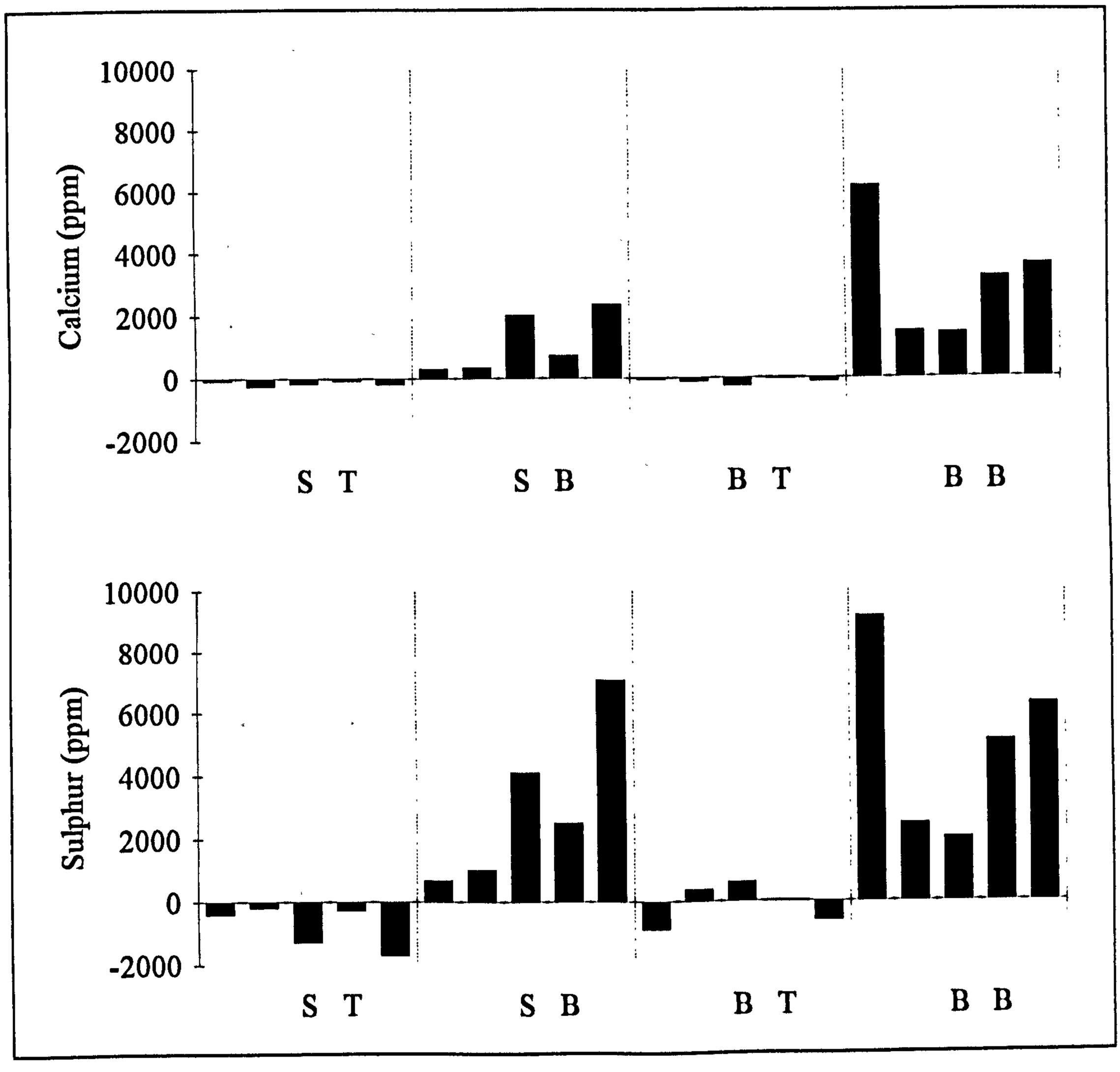

Figure 5.2.16 Changes in the concentration of calcium and sulphur.

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	-157	1155	-129	3187
Standard Deviation	78	968	96	1954
Kurtosis	-2.30	-2.80	0.81	0.51
Skewness	0.09	0.55	-0.99	0.91
Range	178	2056	238	4769
Minimum	-252	306	-278	1414
Maximum	-74	2362	-40	6183
Number of samples	5	5	5	5
Statistical significance of shelter				$p<0.05$
Statistical significance of location				$p>0.05$

Table 5.2.8 Descriptive statistics for changes in calcium concentration (ppm).

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	-784	3081	-105	5004
Standard Deviation	690	2611	646	2938
Kurtosis	-2.08	0.25	-2.24	-0.84
Skewness	-0.75	0.99	-0.24	0.50
Range	1536	6395	1520	7166
Minimum	-1727	683	-903	1999
Maximum	-191	7078	618	9165
Number of samples	5	5	5	5
Statistical significance of shelter				$p<0.01$
Statistical significance of location				$p>0.05$

Table 5.2.9 Descriptive statistics for changes in sulphur concentration (ppm).

Sample group	Correlation coefficient
ST	0.31
SB	0.95
BT	0.67
BB	0.99
All Samples	0.94

Table 5.2.10 Pearsons correlation coefficients between sulphur and calcium.

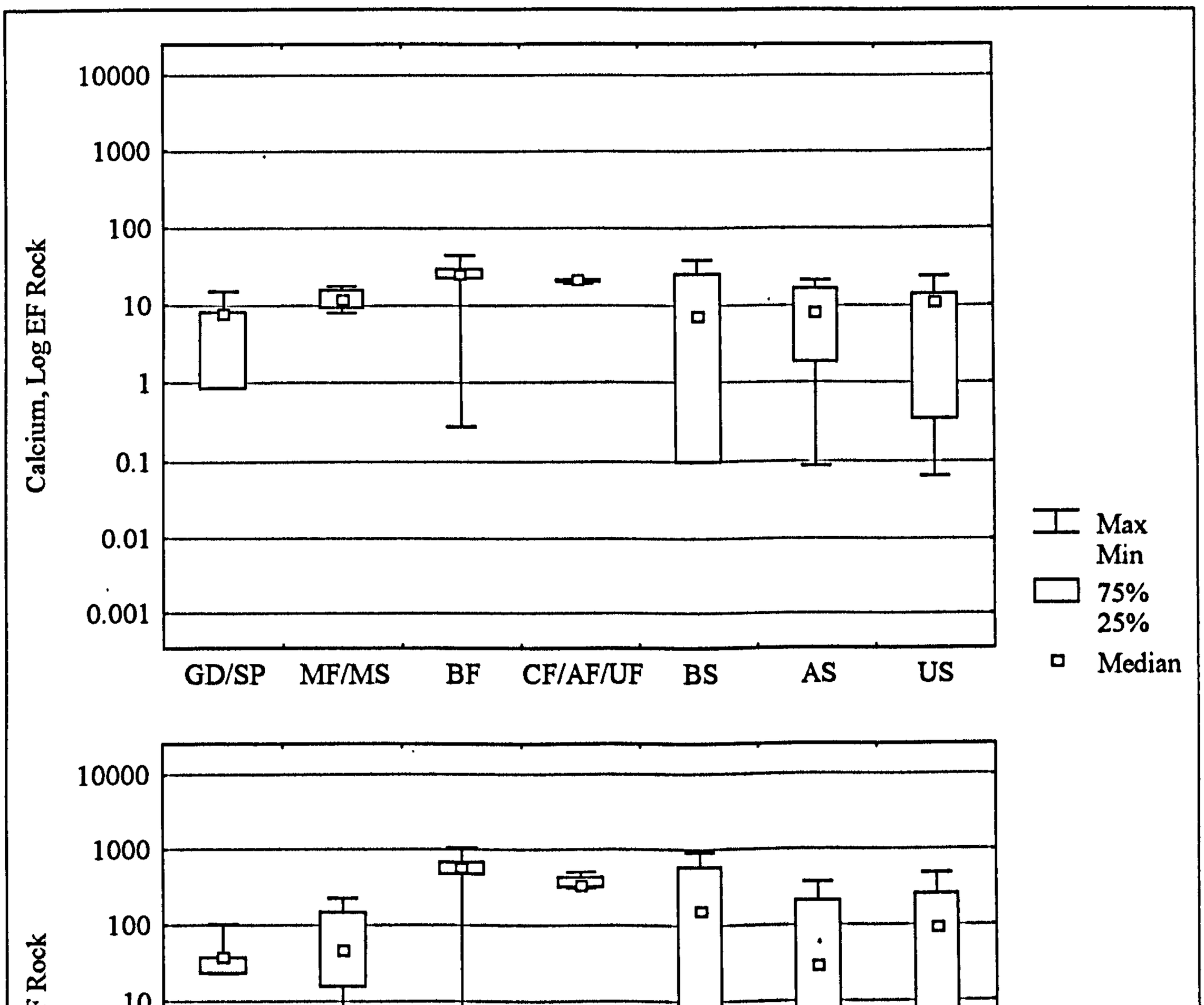

Figure 5.2.17 Enrichment of calcium and sulphur (EF Rock) for sandstones weathered by different forms of weathering (note logarithmic y-axis).

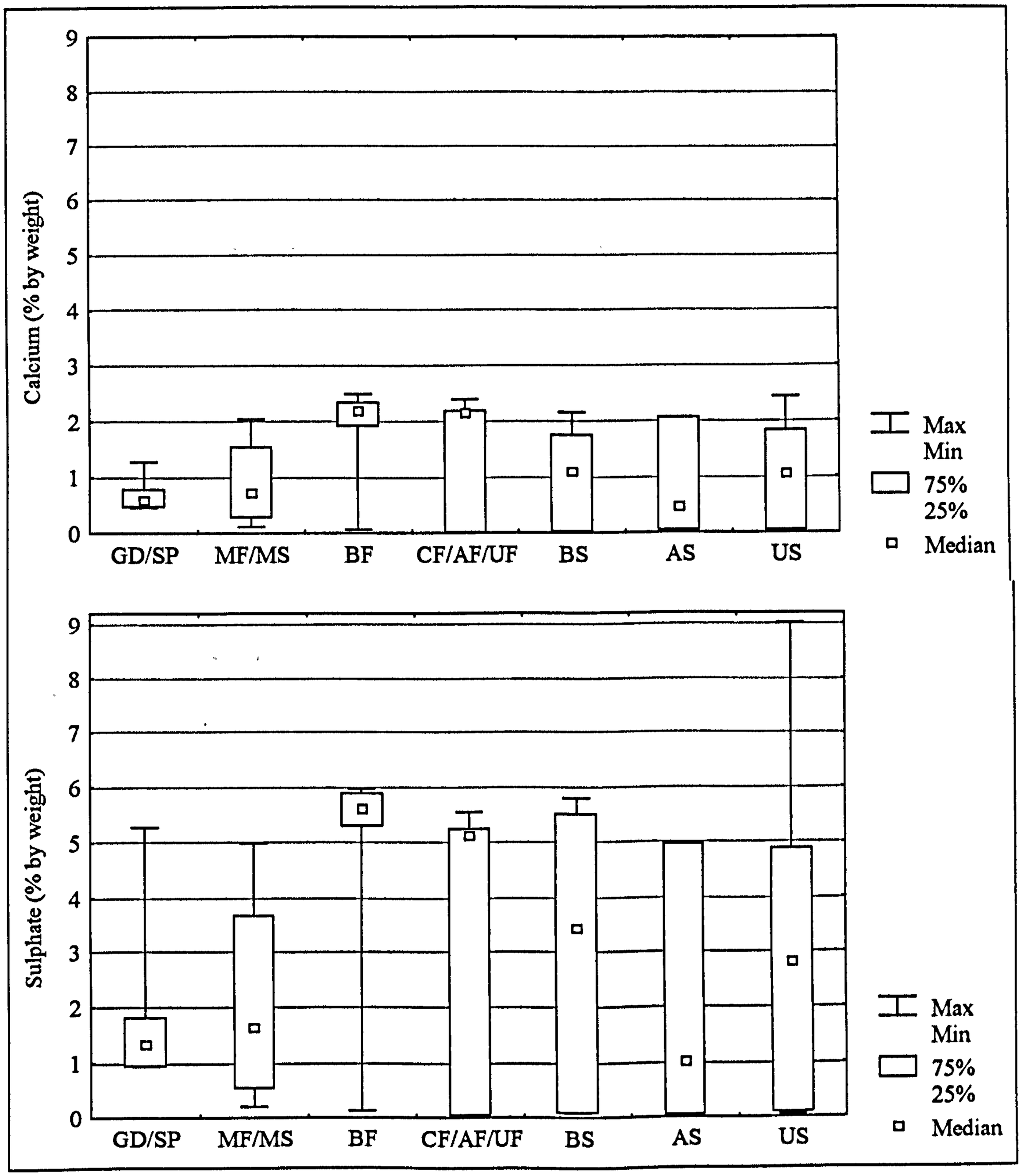

Figure 5.2.18 Concentration of soluble calcium cations and sulphate anions for sandstones weathered by different forms of weathering.

Weathering form	No. of samples	Cl^-	NO^{3-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+
GD	n=4	0.0818	0.1183	2.4187	0.8148	0.1045	0.0317
SP	n=2	0.0646	0.1829	1.3273	0.5900	0.0275	0.0482
MF	n=1	0.0144	0.0362	3.6815	1.5336	0.0048	0.0159
MS	n=2	0.0061	0.0000	0.5468	0.2665	0.0015	0.0075
BF	n=10	0.0547	0.1459	5.1067	2.0056	0.0126	0.0382
CF	n=1	0.0199	0.1070	5.3913	2.0617	0.0090	0.0246
AF	n=2	0.0074	0.0238	2.5474	1.1150	0.0020	0.0127
UF	n=2	0.0179	0.1266	5.3298	2.2682	0.0060	0.0241
BS	n=6	0.0474	0.0822	3.0657	1.0424	0.0084	0.0494
AS	n=4	0.0054	0.0000	2.0065	0.8607	0.0012	0.0078
US	n=12	0.0113	0.0131	2.9107	1.0014	0.0020	0.0118
Mean	n=46	0.0335	0.0737	3.2753	1.2414	0.0155	0.0262

Table 5.2.11 Mean concentration (% by weight) of soluble anions and cations for sandstone exhibiting certain weathering forms.

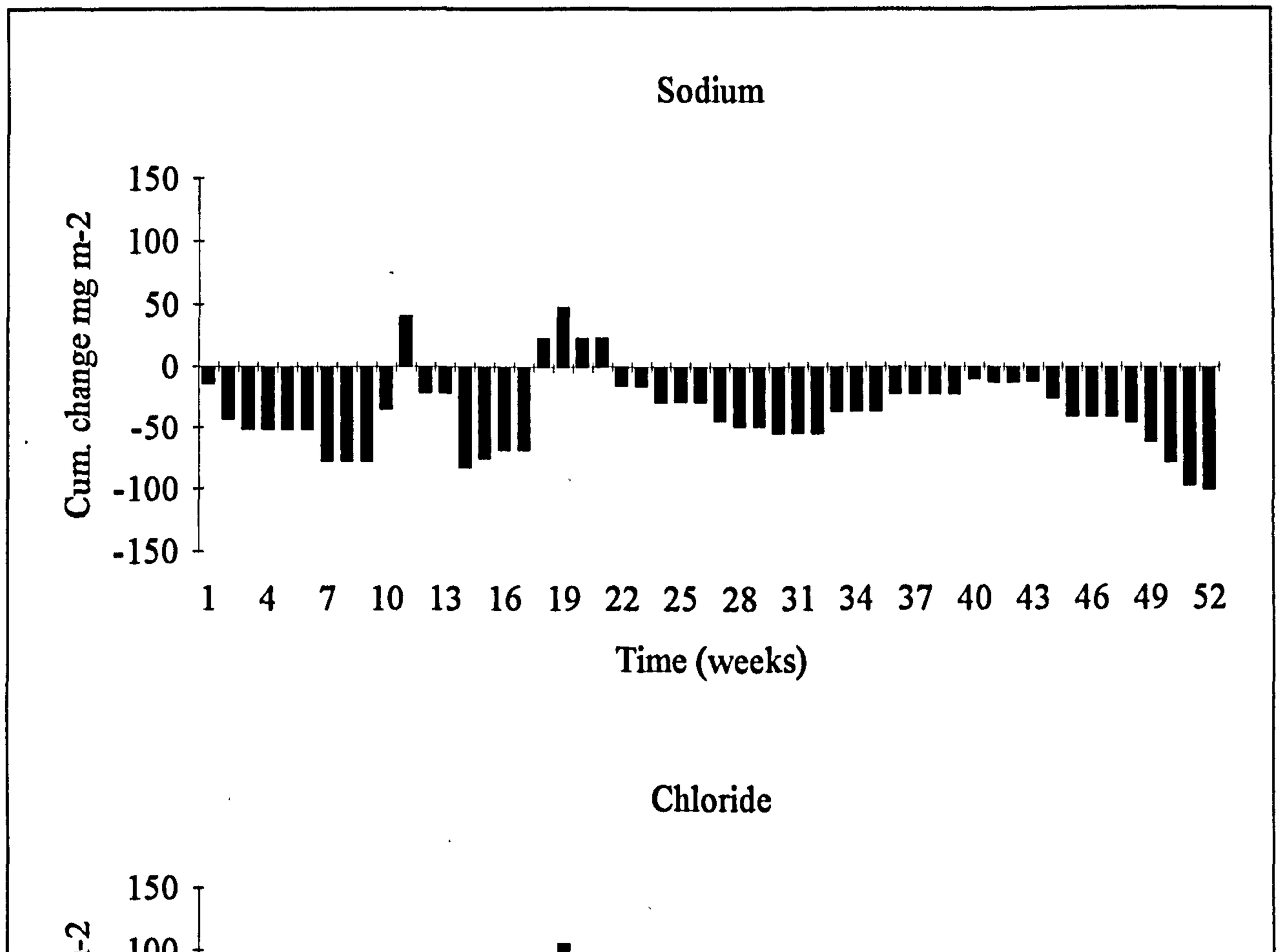

Figure 5.2.19 Cumulative losses and gains (mg m^{-2}) of soluble sodium and chloride.

	GD n=4	SP n=2	MF n=1	MS n=2	BF n=10	CF n=1	AF n=2	UF n=2	BS n=6	AS n=4	US n=12	Mean n=46	Sabbioni & Zappia (1992)* n=7
Al	2.9	1.7	3.7	4.0	4.4	3.3	4.1	4.2	3.0	3.4	3.3	3.6	3.5
C	3.8	0.0	6.7	0.0	8.9	0.0	0.0	0.0	4.7	0.3	9.4	5.8	N/A
Ca	8.1	1.0	12.0	12.9	25.3	19.0	21.2	21.2	14.8	9.3	9.0	14.5	400.0
Cl	24.8	8.8	21.0	25.7	50.3	39.5	30.1	21.8	33.1	18.5	29.1	32.0	N/A
Fe	1.9	1.0	5.0	3.8	2.6	0.9	3.3	2.5	1.9	2.9	2.3	2.5	4.5
K	4.1	3.7	1.4	2.1	6.5	11.8	2.1	2.2	6.1	3.6	4.0	4.6	2.5
Mg	23.2	7.5	17.6	18.8	24.9	15.2	19.3	19.8	18.1	14.3	15.5	18.8	2.0
Mn	6.1	1.1	7.5	10.5	4.0	0.8	10.5	10.2	2.4	8.3	4.1	18.1	N/A
Na	0.8	4589.6	1.0	1.1	4104.5	523.8	1.1	1.2	3627.4	1065.4	505.0	1739.0	N/A
P	2.4	5.5	3.2	2.4	7.4	4.6	6.0	3.8	4.8	2.8	3.7	4.5	N/A
S	50.6	25.5	148.3	15.6	600.2	503.9	346.1	317.0	348.2	107.5	149.2	274.5	40000.0
Si	2.2	1.2	2.7	3.1	2.4	1.7	2.4	2.5	1.7	2.5	2.4	2.3	10.0
V	1.4	1.5	2.1	1.9	2.4	0.1	1.7	0.8	1.6	1.9	1.5	1.7	100.0
Zr	0.9	1.0	1.0	0.7	0.6	0.6	0.1	1.0	0.7	1.1	1.1	0.9	N/A

Table 5.2.12 Mean EF Rock values for sandstone exhibiting various weathering forms. * EF Rocks estimates from a graph by Sabbioni and Zappia (1992).

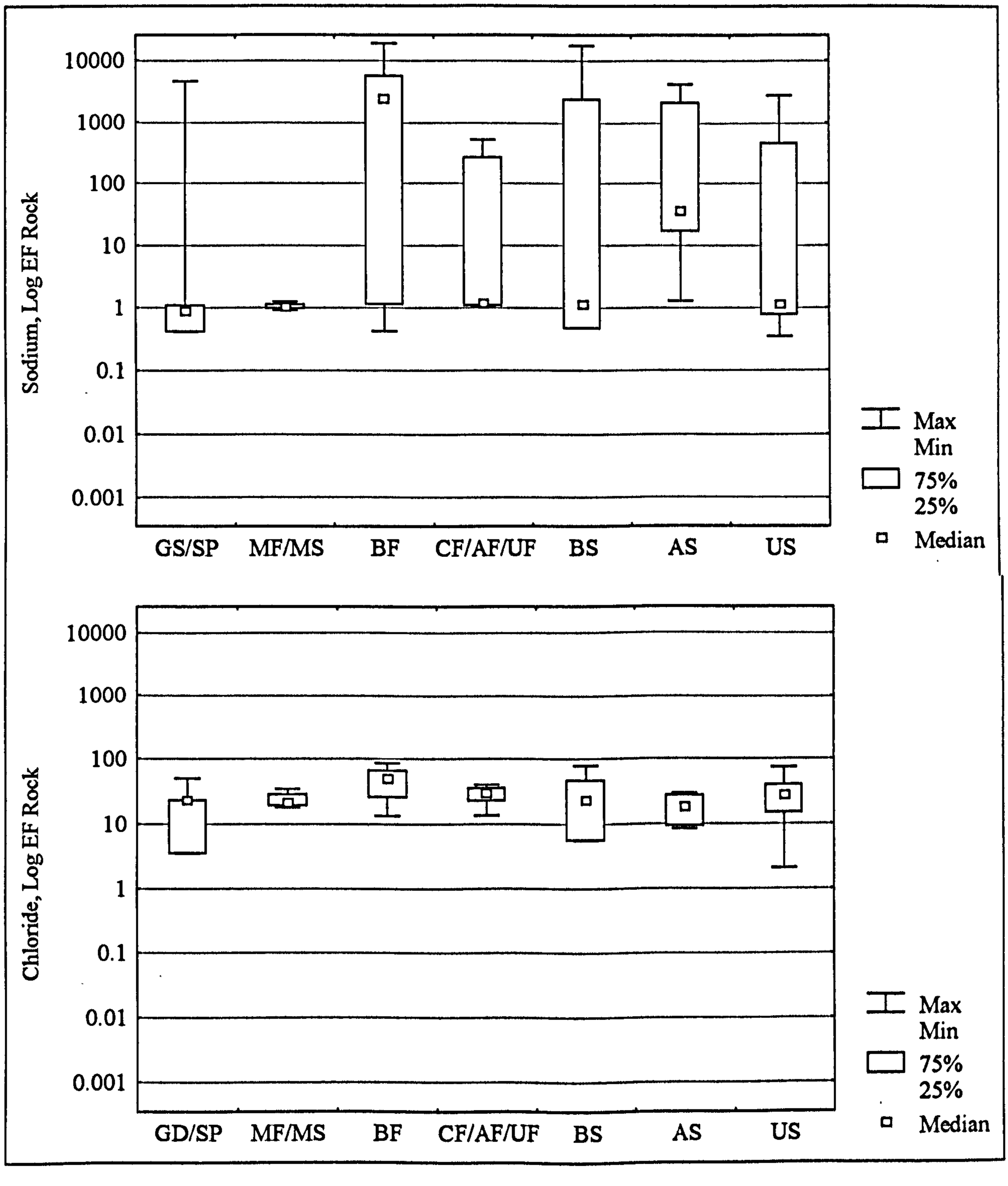

Figure 5.2.20 Enrichment of sodium and chloride (EF Rock) for sandstones weathered by different forms of weathering (note logarithmic y-axis).

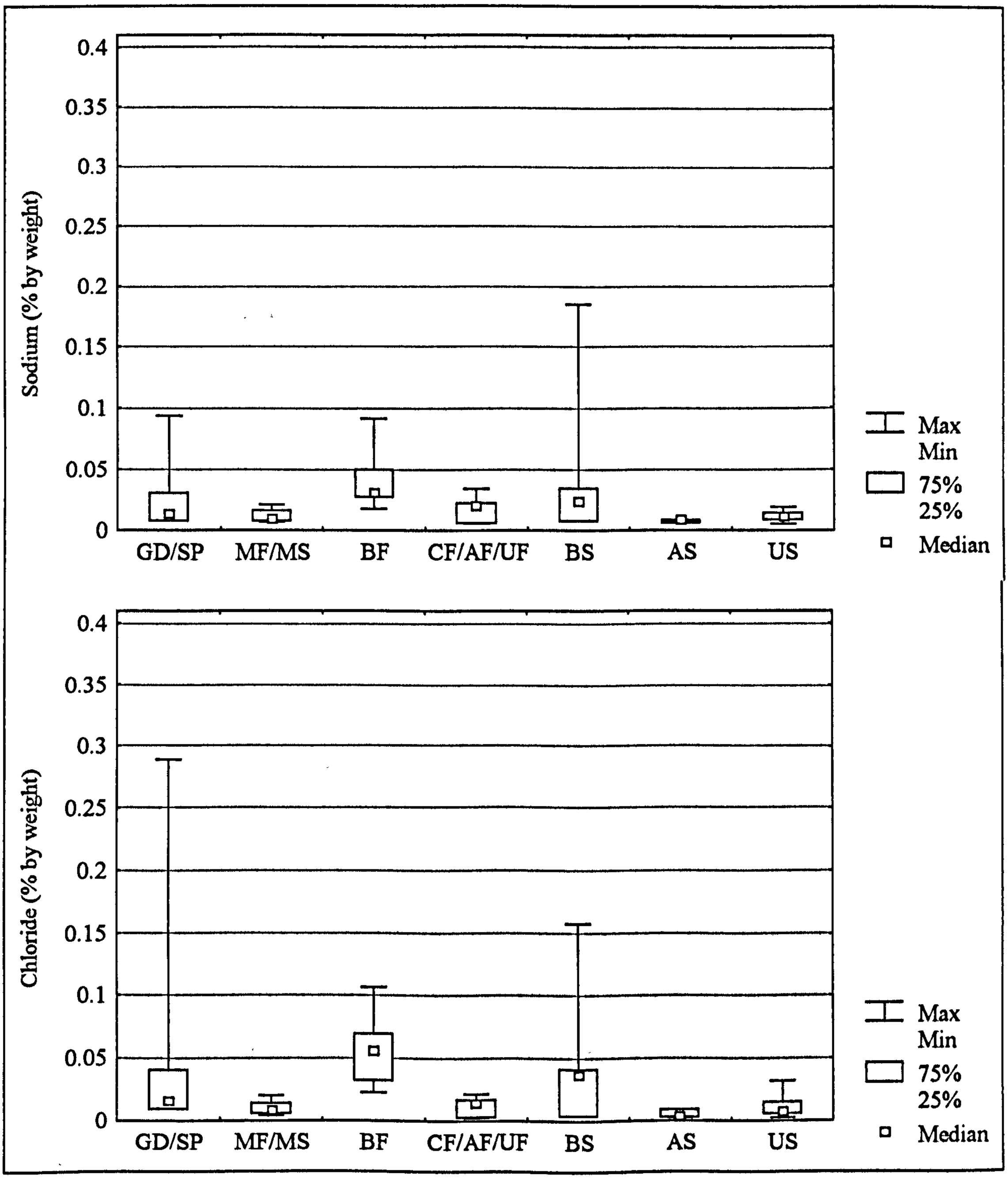

Figure 5.2.21 Concentration of soluble sodium cations and soluble chloride anions for sandstones weathered by different forms of weathering.

A relationship is apparent between the concentration of soluble sodium and soluble chloride (Table 5.2.11). Therefore, the results from the microcatchment experiment and analysis of weathered stone suggests there is a relationship between soluble sodium and chloride, but not total sodium and chloride. Again, black flaking and black scaling have a high concentration, as well as granular disintegration and spalling.

Although halite exerts almost twice the crystallisation pressure of gypsum it is probably less harmful to the sandstone as it does not undergo transitions between hydration states. Also, soluble extractions from weathered sandstone show that sodium and chloride occur in much smaller quantities than calcium and sulphate.

The microcatchment study showed that initially nitrate was lost from the sandstone, but after week 21 it started to gain (Figure 5.2.22). Nitrate was only detected in very small quantities compared to sulphate and chloride, therefore, the microcatchment experiment suggests it is less important in the weathering of sandstone. Soluble extractions from weathered stone show soluble nitrate to occur in similar quantities as for chloride (Figure 5.2.23). The range of concentrations is large for certain weathering forms. As with sulphate and chloride mean concentrations tend to be highest for flaking, especially black flaking (Table 5.2.11). Black scaling also exhibits a relatively high mean concentration.

The microcatchment experiment failed to measure changes in the phosphate. However, the exposure trial showed that phosphorus accumulated slightly in all samples, with greater accumulation in those at Birmingham than those at Preston Montford (Figure 5.2.24). However, there was no statistical evidence ($p>0.05$) for this apparent trend (Table 5.2.13). Phosphates are essential constituents of living organisms, therefore the colonisation of the stone by algae, as discussed earlier, may be responsible for this enrichment. Phosphorus is also used in many manufacturing processes, i.e. fertilisers, matches, glass, china, detergents, food and drink, metal treating, steel and bronze alloys, and electrical components. Therefore, enrichment due to industrial activity must not be discounted and may have accounted for the higher enrichment recorded for the Birmingham samples.

Further evidence for the enrichment of phosphorus is shown by EF Rocks, typically around 4, indicating a slight enrichment (Figure 5.2.25). The EF Rocks are not influenced greatly by different weathering forms, but again flaking, especially black flaking, and black scaling have relatively high mean enrichments. If the phosphorus enrichment was related to autotrophic growth, it would be expected that stone weathered by autotrophic flaking and autotrophic scaling would have markedly higher EF Rocks for phosphorus. However, this is not the case. Also, samples at Birmingham gain more phosphorus than those at Preston Montford and Section 4.2.3 shows that autotrophic growth is predominantly greater in rural areas than urban areas. These observations indicate that air pollution may be more important than autotrophic growth in the formation of phosphate salts.

The microcatchment experiment found a small, but significant ($p<0.05$) accumulation of magnesium in the sandstone (Figure 5.2.26). The results for the exposure trial agree well with those from the microcatchment experiment, with magnesium gaining in all samples (Figure 5.2.27). An apparent trend suggests that sheltered samples gained more magnesium than exposed ones. However, there is no statistical evidence ($p>0.05$) for this effect or for an influence of location (Table 5.2.14). EF Rocks for weathered stone shows that magnesium has a reasonable amount of enrichment (mean EF Rock 10). For soluble magnesium to have accumulated in the stone it must have formed insoluble compounds. Soluble extraction of magnesium for weathered sandstone shows that very little of the magnesium is soluble. Therefore, it may be the case that magnesium is binding to clays contained in the sandstone and therefore becoming fixed in the stone. It therefore seems unlikely that magnesium is involved in the formation of salts.

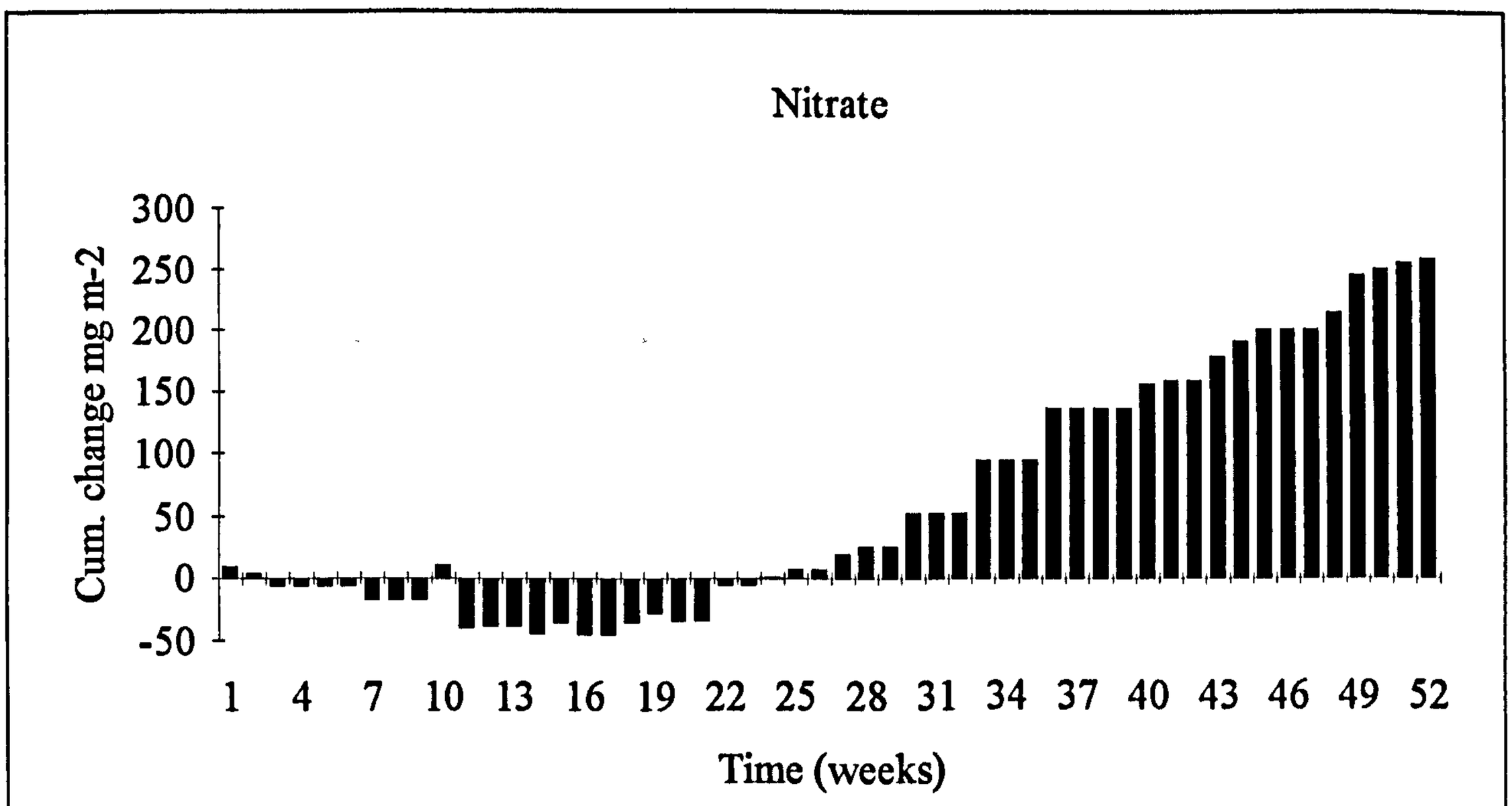

Figure 5.2.22 Cumulative losses and gains (mg m^{-2}) of soluble nitrate.

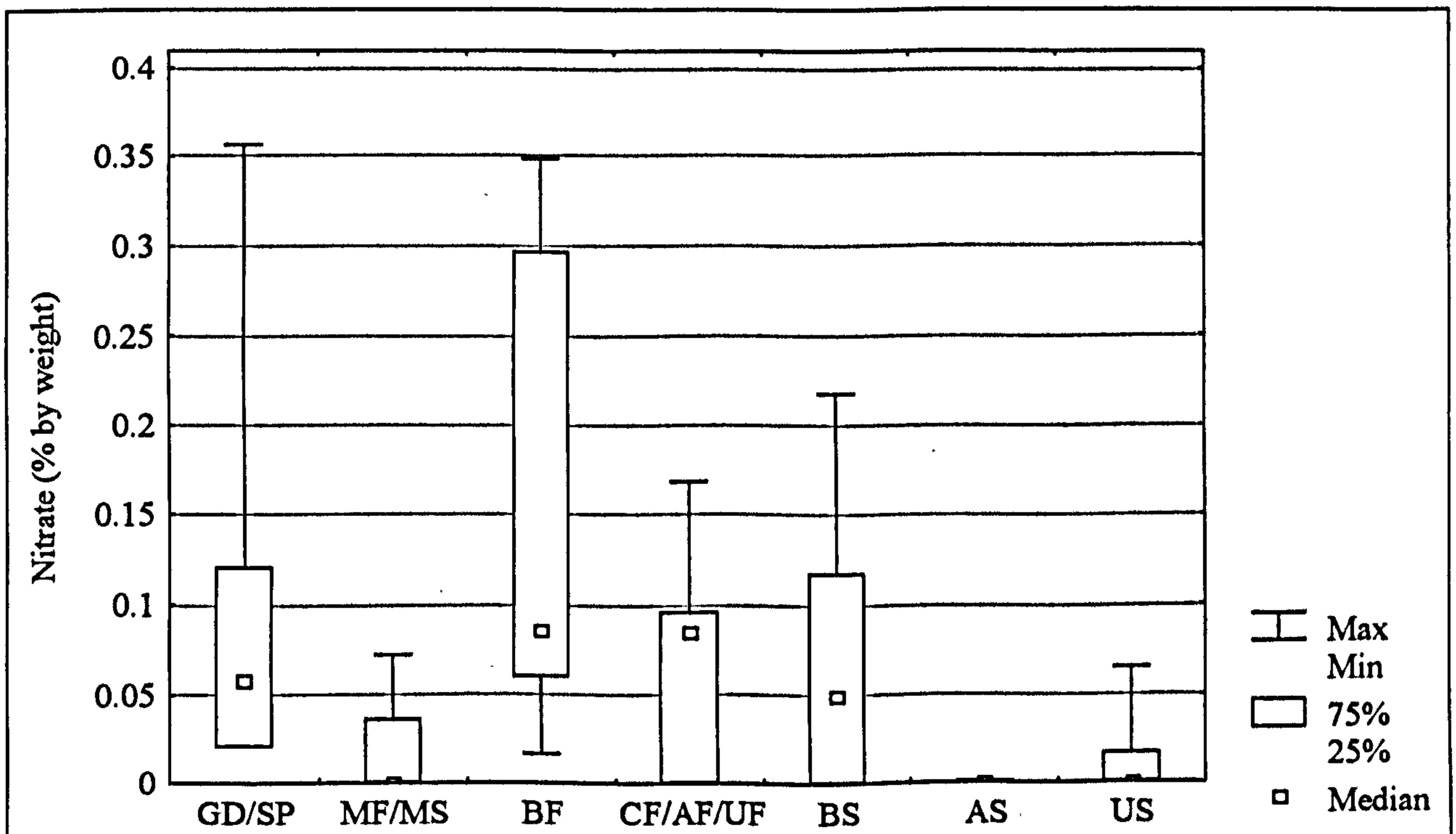

Figure 5.2.23 Concentration of soluble nitrate anions for sandstones weathered by different forms of weathering.

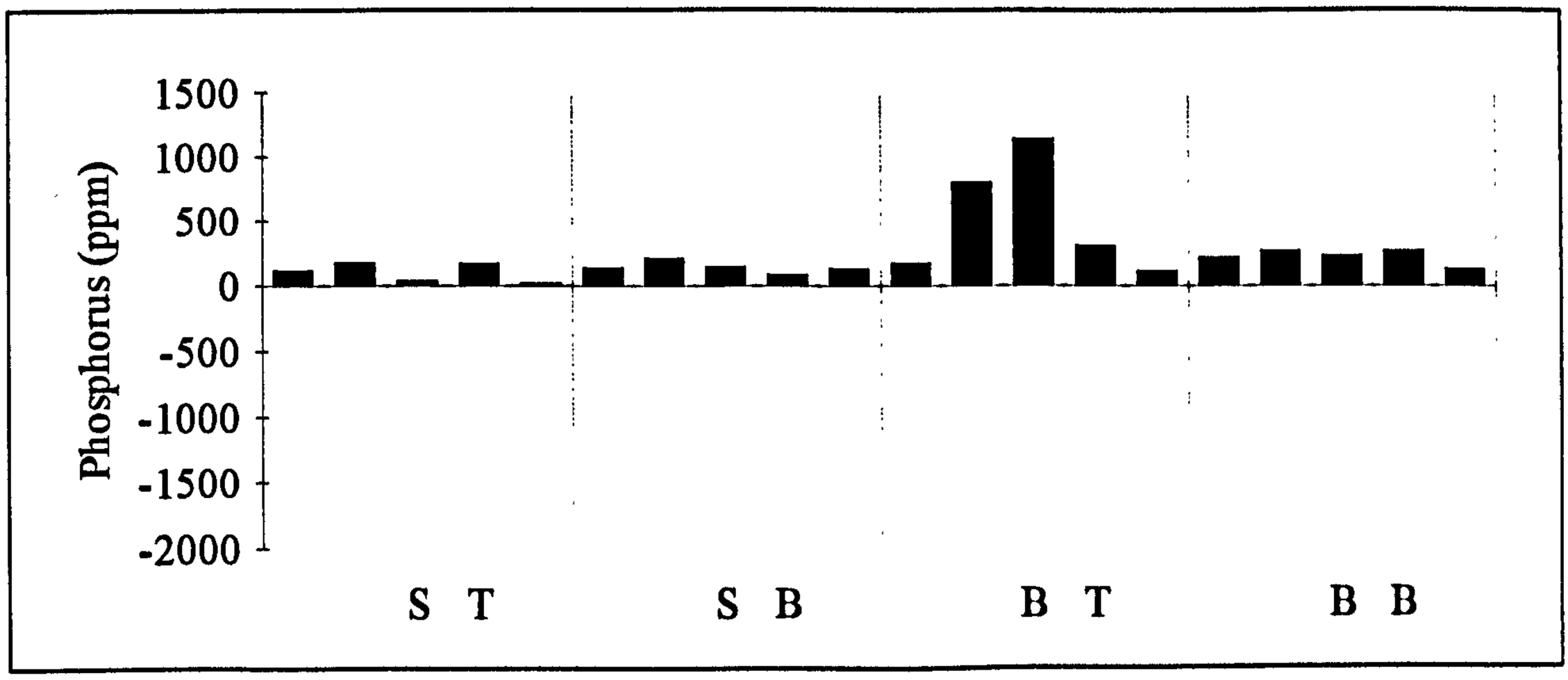

Figure 5.2.24 Changes in the concentration of phosphorus.

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	111	146	516	234
Standard Deviation	73	45	445	60
Kurtosis	-2.84	2.04	-1.48	2.28
Skewness	-0.27	0.55	0.80	-1.47
Range	159	127	1026	148
Minimum	26	87	120	135
Maximum	185	215	1147	283
Number of samples	5	5	5	5
Statistical significance of shelter				p>0.05
Statistical significance of location				p>0.05

Table 5.2.13 Descriptive statistics for changes in phosphorus concentration (ppm).

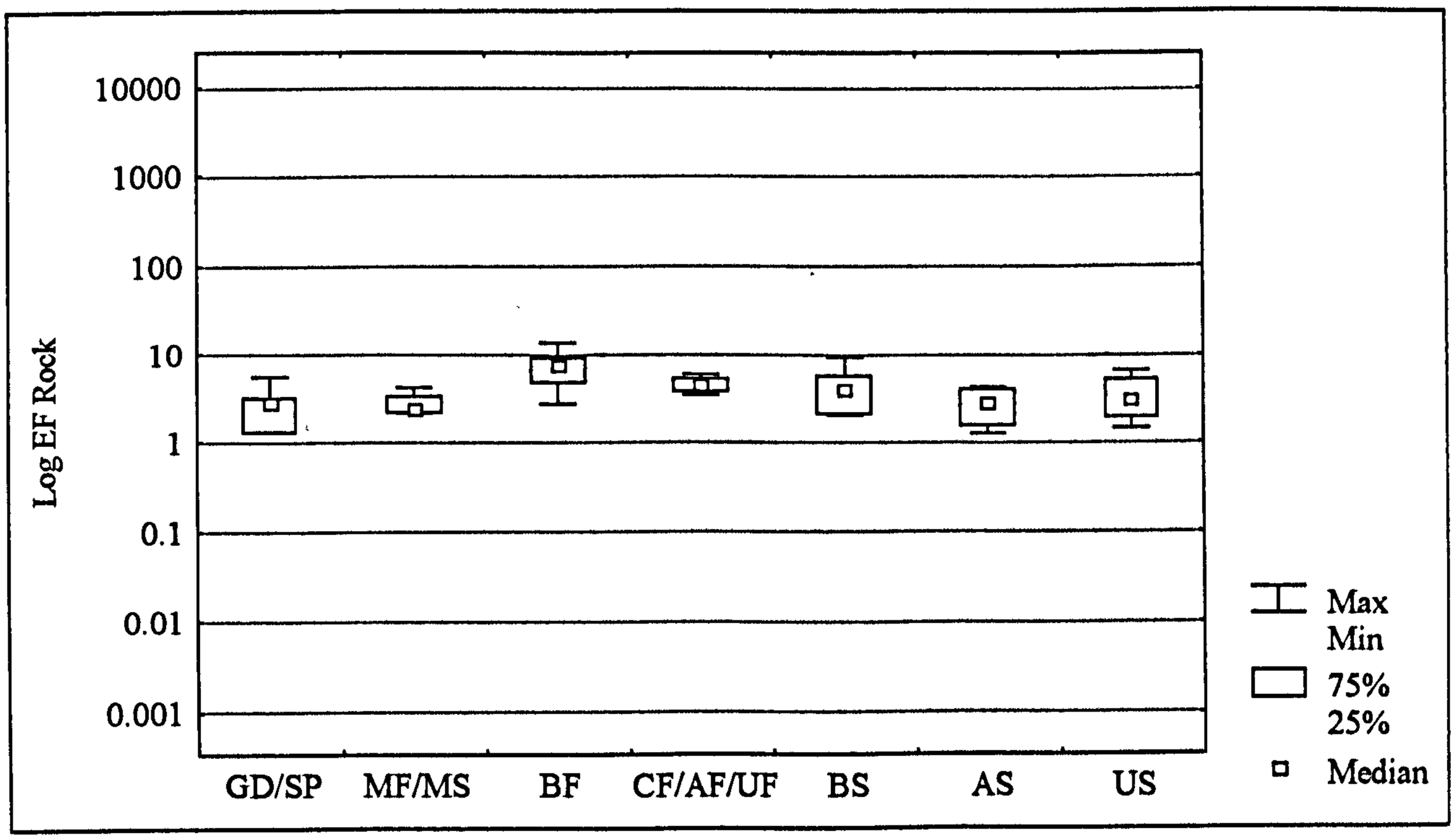

Figure 5.2.25 Enrichment of phosphorus (EF Rock) for sandstones weathered by different forms of weathering (note logarithmic y-axis).

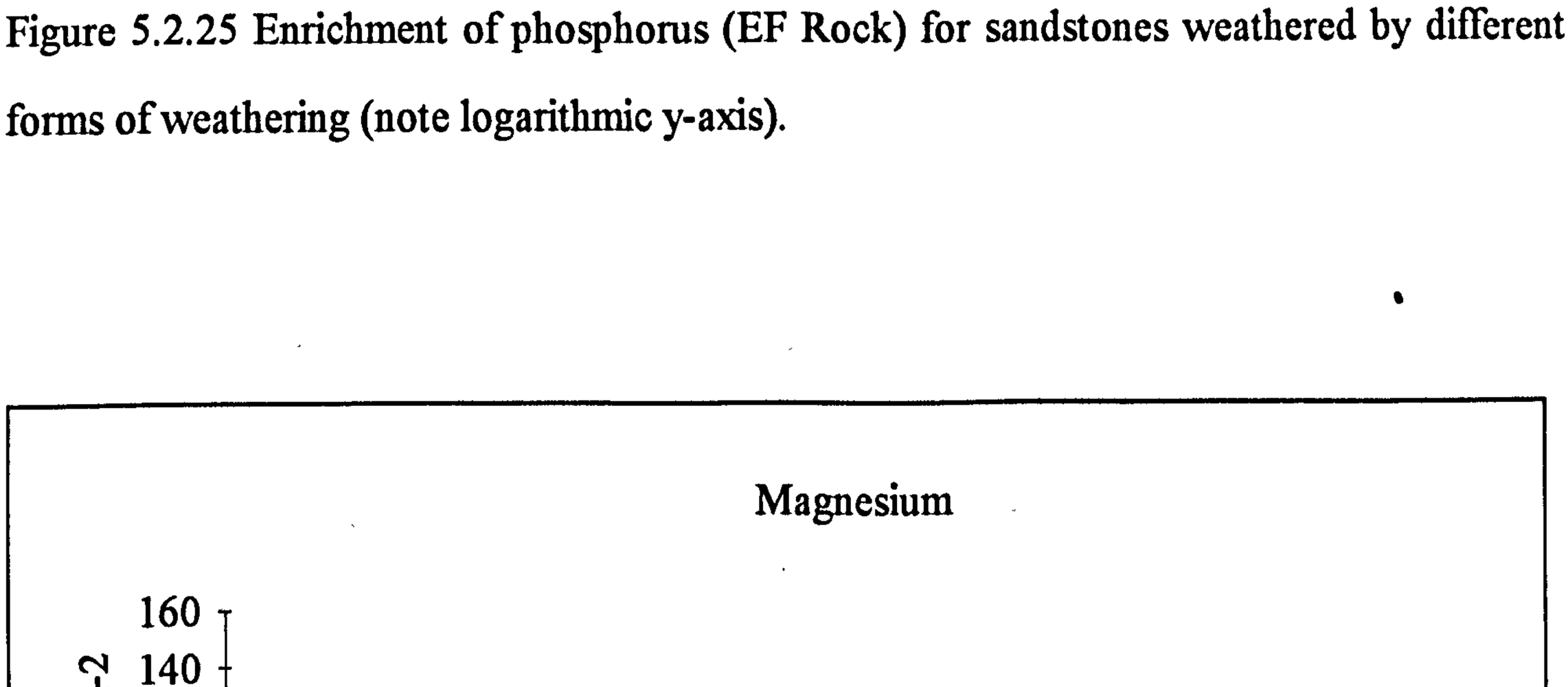

Figure 5.2.26 Cumulative gains (mg m^{-2}) of soluble magnesium.

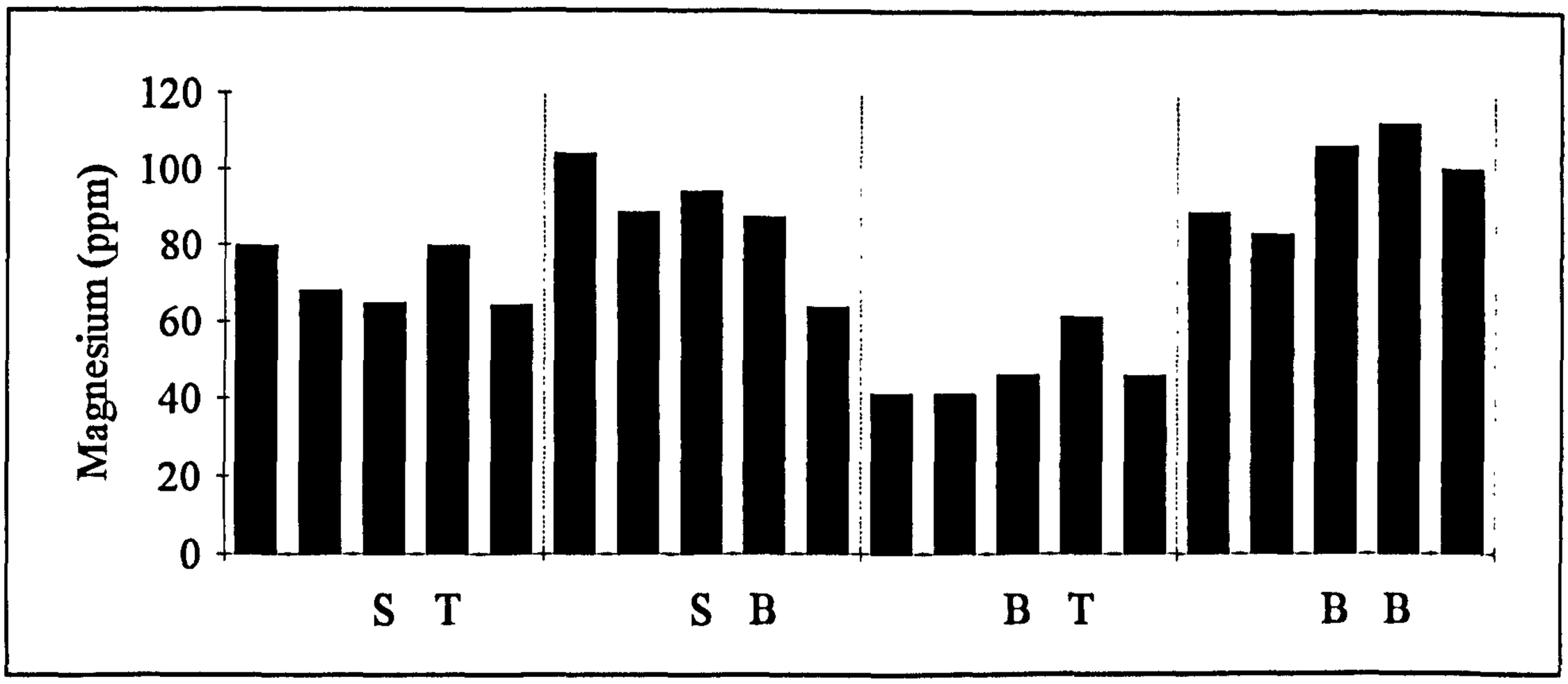

Figure 5.2.27 Changes in the concentration of magnesium.

	October 1993 to February 1995			
	ST	SB	BT	BB
Mean	71	88	47	99
Standard Deviation	8	15	8	12
Kurtosis	-3.16	2.20	3.28	-1.94
Skewness	0.45	-1.11	1.74	-0.21
Range	15	41	20	29
Minimum	64	64	41	84
Maximum	80	104	62	113
Number of samples	5	5	5	5
Statistical significance of shelter				p>0.05
Statistical significance of location				p>0.05

Table 5.2.14 Descriptive statistics for changes in magnesium concentration (ppm).

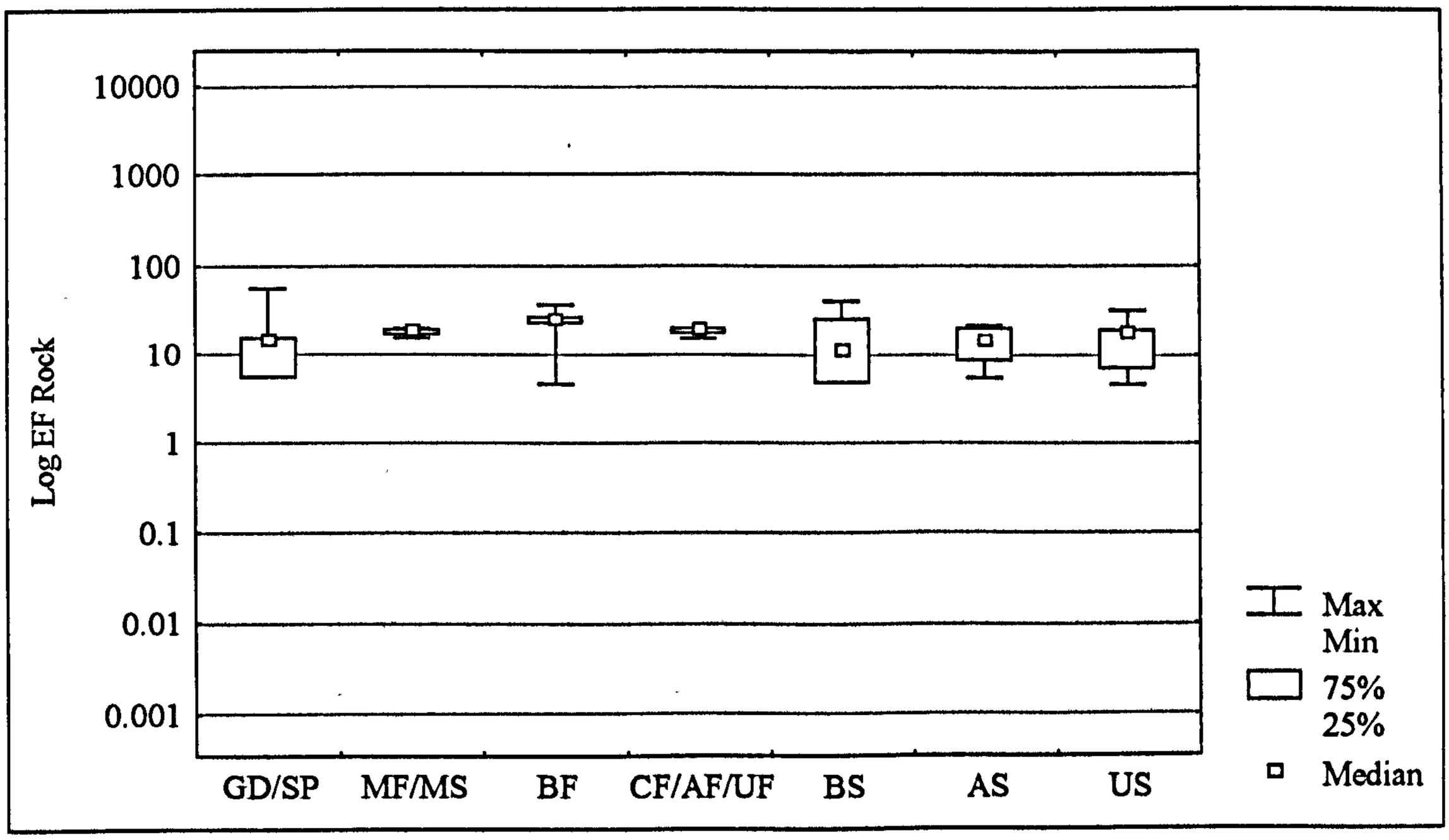

Figure 5.2.28 Enrichment of magnesium (EF Rock) for sandstones weathered by different forms of weathering (note logarithmic y-axis).

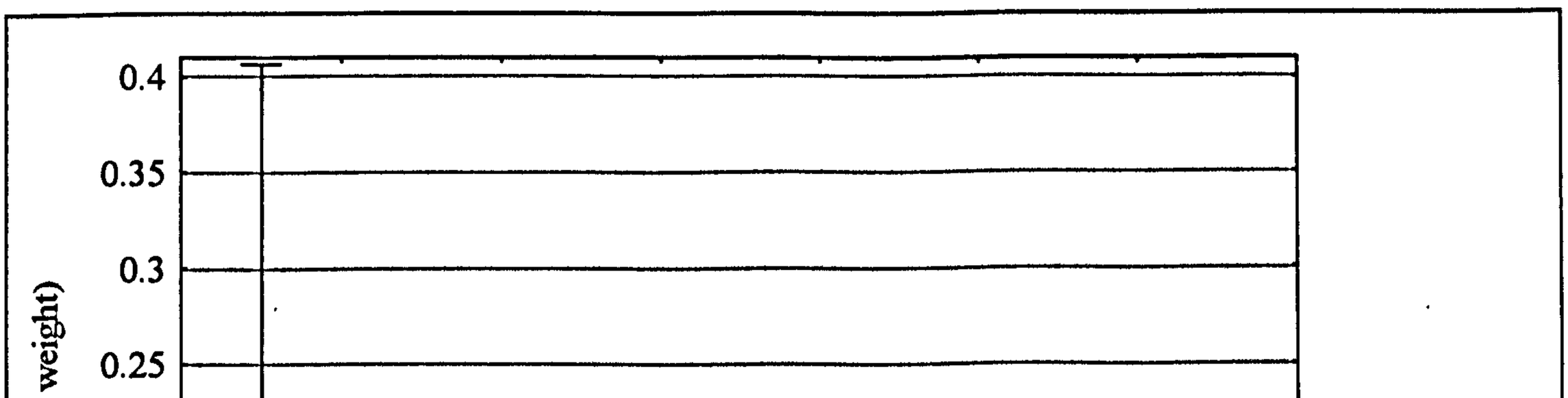

Figure 5.2.29 Concentration of soluble magnesium cations for sandstones weathered by different forms of weathering.

5.3 IMPLICATIONS FOR METHODS USED IN STONE WEATHERING STUDIES

To assess chemical alterations due to sandstone weathering three complementary methods (microcatchments, exposure trials and analysis of weathered stone) have been selected to provide information on specific areas of sandstone weathering. In addition to this, the use of three different methods provides a means to critically appraise each of them.

The microcatchment experiment is a very valuable and precise technique which provides a great deal of information from short-term measurements. However, due to the necessity for runoff to be generated, only information on stones in exposed positions is gained. Exposure trials are not restricted by this limitation and can therefore be used to examine the influence of shelter. Also, the low maintenance requirements of exposure trials enables them to be sited in remote areas. This includes positioning on selected parts of buildings, for example, Whalley, *et al.* (1992).

Comparing the results from the exposure trial to those obtained from the analysis of weathered stone suggests that stones in buildings weather in a similar manner to the sheltered samples rather than the exposed ones. For example, calcium and sulphur were typically lost from the samples in exposed positions (Figure 5.2.14). However, weathered sandstone showed an enrichment of both calcium and sulphur (Figure 5.2.15), as did samples in sheltered locations (Figure 5.2.14).

The analysis of weathered stone provides very valuable information on how stones in buildings have weathered over longer time periods. The calculation of enrichment factors (EF Rocks) appears a valid and informative way of calculating chemical changes. However, it must be remembered that the technique is based on the assumption that the original ratio of each element to titanium is the same as a determined average. Obviously this assumption may be violated due to the heterogeneous nature of sandstones, but the incidence and extent of violations are hard to determine. The other major assumption made for the calculation of EF Rocks is that titanium is stable and not influenced by the weathering of the stone. Titanium is usually present in sandstones in clays and sometimes the heavy minerals rutile,

ilmenite, brookite and anatase (Pettijohn, 1972). Zirconium, usually present as detrital minerals, such as zircon, is an alternative element to titanium as it is also relatively stable. An indication of the appropriateness of titanium and zirconium for calculating EF Rocks can be obtained by investigating the EF Rock for zirconium (i.e. the enrichment of zirconium compared to titanium). Results show that some variability exist in the EF Rocks obtained (Figure 5.3.1). However, the average EF Rock for zirconium is very close to one (Table 5.2.12) for all weathering forms. Therefore, if a reasonably large sample size is available the use of zirconium and titanium to calculate absolute elemental changes appears valid.

The results from the exposure trial for titanium and zirconium did not follow the expected pattern (Figure 5.3.2). As the results are relative changes, a relative loss would be expected for titanium and zirconium in sheltered positions, due to the dilution effect caused by atmospheric deposition, while a relative gain would be expected in exposed positions, due to a concentration effect caused by the dissolution of certain elements (Section 5.2.2). This is not the case and titanium shows relatively large changes in concentration. Increases in titanium may be due to inputs of titanium from atmospheric deposition. Indeed, Cheng *et al.* (1976) reports that titanium is a major component of glassy spheres from coal combustion (Table 5.2.1). However, the loss of titanium from some of the samples exposed in Preston Montford can not be accounted for. Zirconium is not generally a constituent of fly ash or other atmospheric pollutants, therefore it should be appropriate for calculating absolute elemental changes in polluted environments. Indeed, the changes in zirconium concentration are less than for titanium. However, as with titanium, the changes do not follow the expected pattern had zirconium remained stable during weathering. Therefore, the use of titanium and zirconium for calculating absolute elemental changes at these concentrations using this technique is inappropriate. As mentioned for the calculation of EF Rocks a larger sample size may overcome this problem and indeed zirconium appears more appropriate than titanium (Figure 5.3.2).

5.4 SUMMARY

The contributions presented in this chapter to identifying and explaining the mechanisms and weathering forms responsible for the weathering of sandstone buildings in the West Midlands are summarised below.

a) A range of atmospheric particles accumulated on the surface of the sandstone. These particles contained, in order of decreasing concentration, silicon, aluminium, iron, calcium, magnesium, sodium and potassium. Fly ash from coal and oil combustion were the dominant atmospheric deposits and may therefore be an important cause of sandstone soiling.

b) The exposure trial suggested that samples in sheltered positions retained more of the deposited atmospheric particles than samples in exposed positions. This is supported by the microcatchment experiment, which showed a positive correlation between particulate loss and runoff volume.

c) Silicate minerals, such as orthoclase, undergo hydrolysis which was most marked in exposed positions. Orthoclase hydrolysis causes clay formation, which under the acidic conditions experienced in this study, results in a 1 N mm^{-2} reduction in strength in about 60 years. Under alkali conditions swelling clays may form, which may cause disruptive pressures on the stone.

d) Dissolution of silica was detected by the microcatchment experiment, however analysis of weathered stone showed an enrichment of silica. This may have been due to the more sheltered location of stones incorporated into buildings or due to the dissolution of silica from the subsurface of the stone, which then precipitated at the surface.

e) The microcatchment experiment, exposure trial and analysis of weathered stone collected from buildings, suggested that gypsum formation was widespread. This may be due to sulphation of calcium contained in the stone, as well as atmospheric deposition. Gypsum was lost from exposed locations, but accumulated in sheltered locations. Stone weathering

by flaking and scaling, especially black scaling and flaking, had particularly high gypsum concentrations. Gypsum may cause weakening of the stone, due to the loss of cementing material, and create disruptive pressures by crystallisation and hydration.

f) The microcatchment experiment suggested that small quantities of halite formed in the sandstone. Both sodium and chloride were enriched in weathered stone, especially black flaking and scaling, spalling and granular disintegration. Halite may cause disruptive pressure on the stone by crystallisation.

g) Some evidence exists for the formation of nitrate salts, but in smaller concentrations than sulphates and chlorides. Stone weathered by black flaking and scaling experienced relatively high nitrate concentrations.

h) The exposure trial showed that phosphorous accumulated in the stone, which is supported by a slight enrichment of phosphorus in weathered stone, especially for black flaking and scaling. Autotrophic activity does not appear to increase the phosphorus concentration, but it may be increased by industrial activity.

i) No evidence was found for a difference between urban and rural locations. However, the effects of shelter were found to be significant for eight elements.

j) In some cases the results obtained from the exposure trial differ from those obtained with the microcatchment experiment. This may have been caused by the higher surface area to volume ratio of the exposure trial samples, compared to the microcatchments. An alternative cause may be due to XRF only detecting changes in the surface layer of the stone, which differ from the bulk chemical changes detected with the microcatchment experiment.

k) Analysis of weathered stone collected from buildings suggested that the weathering of stones incorporated into buildings is more similar to samples exposed in sheltered positions than samples in exposed positions.

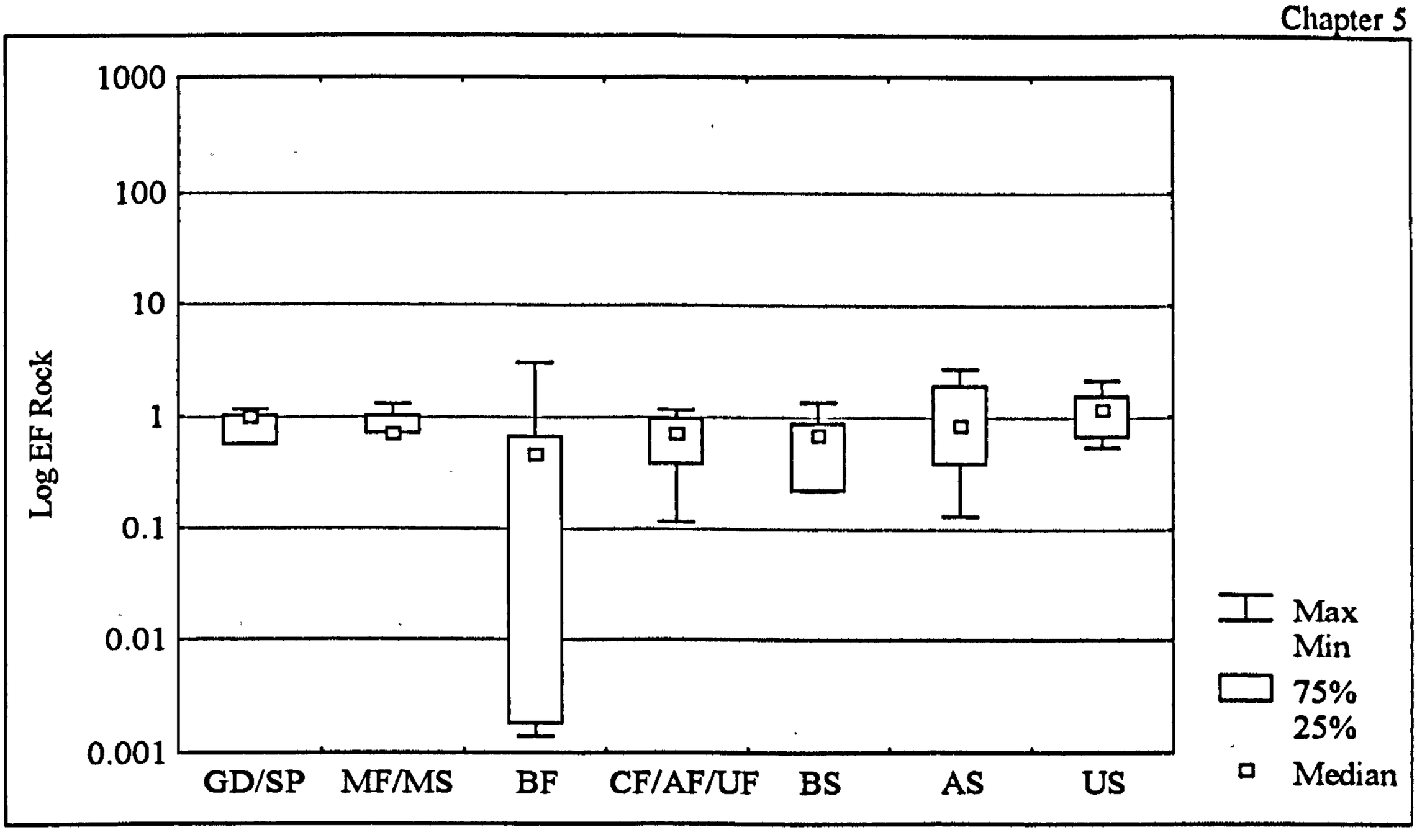

Figure 5.3.1 Enrichment of zirconium (EF Rock) for sandstones weathered by different forms of weathering (note logarithmic y-axis).

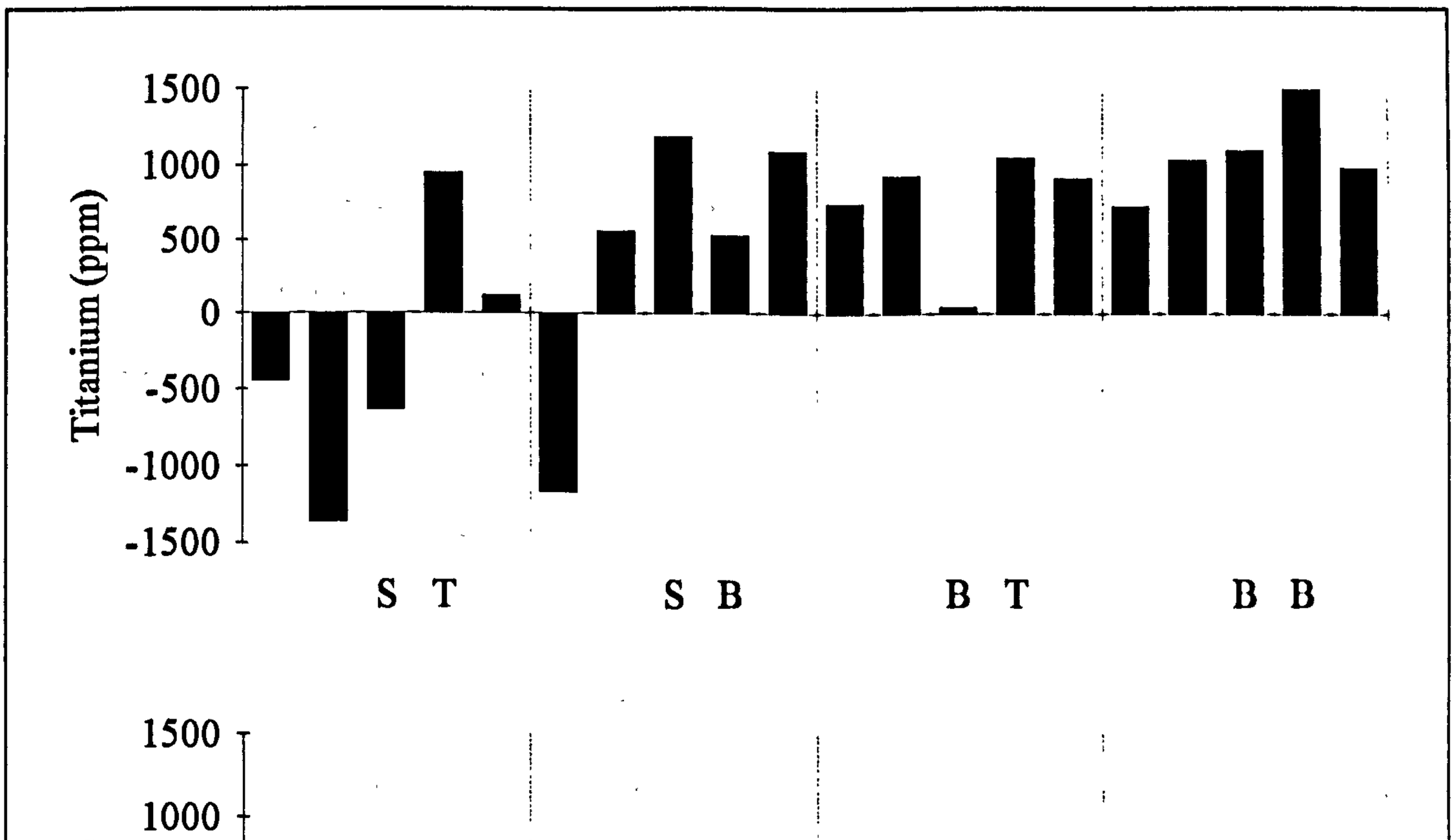

Figure 5.3.2 Changes in the concentration of titanium and zirconium.

CHAPTER 6

ELUCIDATION OF THE MECHANISMS INVOLVED IN THE WEATHERING OF SANDSTONE BUILDINGS

6.1 INTRODUCTION

The results from the experiments detailed in Chapters 4 and 5, show that sandstones experience chemical and physical alterations which cause weathering. Results also show that differences in the importance of these alterations cause spatial variations in sandstone weathering, from a micro to a macro scale. Some of the experiments provide statistically significant results, while in other cases apparent trends may suggest an influence which can be inferred by examining the results from several experiments. Where the results from more than one experiment are used, it must be borne in mind that differences exist in the temporal scales between the various experiments. These different scales allow the evaluation of some very specific data, collected over a short period of time, alongside some less specific data concerning weathering over a long time period. This provides a greater insight into stone weathering and therefore improves the accuracy of inferring weathering mechanisms. When considering the mechanisms responsible for creating certain sandstone weathering forms, it is apparent that the mechanisms are not isolated from each other and may have interactive or synergistic effects. It is the aim of this chapter to elucidate the mechanisms which bring about specific weathering forms.

6.2 BLACK SOILING, BLACK FLAKING AND BLACK SCALING

Blackened stone (the sum of black soiling, black flaking and black scaling) was present in 86% of the quadrats and accounted for 33% of the total weathering recorded by the building survey. The black colouration of the stone is commonly attributed to the deposition of soots and fly ash particles. Scanning electron microscopy of black scales, collected from St. Bartholomew Church, Wednesbury (C3), near the centre of the West Midlands conurbation (Figure 4.2.16), showed the presence of a range of particulate matter (Plate 6.2.1). However, coal fly ash, identified by its glassy and spherical form (Cheng *et al.*, 1976) was found to be the dominant atmospheric deposit. This is not surprising, since historically the local source of fuel was the local Carboniferous Coal Measures (Section

3.2.3). The building survey provided convincing evidence that the deposition of atmospheric particles causes the blackening of stone, which was greatest close to heavy industry. The microcatchment experiment and exposure trial showed that the deposition of particulate matter, especially fly ash, is still active in the West Midlands. However, the exposure trial failed to detect an urban/rural contrast, possibly because the exposure time was not sufficient to measure this effect. However, much of the urban to rural contrast detected by the building survey may be the result of past atmospheric pollution levels. Therefore, the effect may be reduced under today's environmental conditions of the West Midlands, due to changes in the concentration and nature of pollutants.

The dominance of atmospheric deposition, causing black soiling, has been questioned by microbiologists, in particular Krumbein (1992) and Gorbushina *et al.* (1993). Krumbein (1992) found that on a black soiled surface, less than 1% of the surface area was covered by atmospheric particles. According to Krumbein (1992), the origin of this black soiling was biological, with fly ash and soot as secondary influences. However, the author failed to provide a percentage of cover of biological materials or provide any evidence that it was greater than the cover of fly ash. Possible biological influences include iron and manganese oxidising fungi, and Dematiaceae (black fungi), which produce fungal spores similar in appearance to fly ash when viewed with a SEM. The importance of black fungi was examined further by Gorbushina *et al.* (1993) who reported their occurrence in large numbers on many stone types, including sandstones. SEM examination of sandstone samples from the West Midlands showed structures very similar to the black fungi documented by Gorbushina *et al.* (1993), to be present on many samples. In some cases these micro organisms were observed attached to fly ash particles (Plate 5.2.2) and penetrating into mineral surfaces (Plate 5.2.3). However, in terms of the percentage of surface cover, the importance of fly ash generally outweighed that of biological material (Plate 6.2.1). Published literature and personal communications with Prof. W. Krumbein, a geomicrobiologist pioneering much of the work on fungal colour changes to stone, fails to explain if black fungi may increase due to atmospheric pollution. Consequently, the increase in black soiling related to atmospheric pollution, as shown by the building survey, is important evidence that atmospheric pollution levels are important in generating black

soiling. It appears likely that fungi play a role in the blackening of stone, but in this study the deposition of particulate matter was the dominant cause.

Sabbioni and Zappia (1992) noted that blackening of the stone was independent of the geometry of the building and exposure. However, the results from the building survey contradict this and indeed, blackening showed a greater occurrence on the south and west aspects. Section 4.2.2 notes that the deposition of particles by thermophoresis and Stefan flow is less on these aspects, compared to the north and east. However, inertial impact and increased wet deposition of particles may be higher for these aspects. This may be responsible for the greater occurrence of blackening on the south and west aspects. However, a further consideration is the depth water absorbs into the stone. Observations on buildings show that horizontal stones experience much more black soiling than vertical stones (Plate 6.2.2). Due to the horizontal position, gravity increases the absorption of water, which carries particles into the pores of the stone. The same mechanism may operate on vertical stones, hence those receiving the greatest absorption will experience the greatest blackening. On walls receiving distinct wetting-drying cycles, absorption of precipitation may be greater than stones that are more constantly wet. Results from Lichfield Cathedral showed that stones on the south and west aspects become very dry and then receive considerable precipitation, often wind-driven. Absorption of this water will be rapid due to the capillary action exerted by the very dry stone, but also due to the inertia imparted by the wind. As the water is absorbed it carries particles which have been deposited on to the stone, into the pore structure. When incoming precipitation exceeds infiltration, runoff occurs. However, at this time many of the particles are lodged in the pores of the stone and surface runoff fails to remove them. In contrast, stones on the north and east aspects do not receive such distinct wetting-drying cycles, therefore absorption, due to capillary action and wind-driven rain, is reduced. Consequently, absorption is not as rapid, so particles are not carried into the pores of the stone allowing runoff to remove them.

Examination of weathered stone showed that atmospheric particles deposited onto sandstone were rich in silicon, aluminium, sulphur, calcium, potassium and iron (Figure 5.2.5 and Figure 5.2.6). On sandstones, with little calcareous material, deposition of

particulate matter may be an important source of calcium necessary for gypsum formation. Furthermore, the deposition of atmospheric particles containing iron, may catalyse gypsum formation. Indeed, Elfving *et al.* (1994) described the possible mechanism by which manganese, as well as iron, may increase sulphation of stone. Further evidence of this is shown by the mean calcium and sulphur EF Rocks, which are greater for black flaking and black scaling, than other forms of flaking and scaling (Table 5.2.6). Obviously elevated levels of gypsum formation will increase stress in the stone, imposed by salt weathering mechanisms.

In addition to salt weathering, atmospheric soiling may increase stone deterioration by enhancing other physical weathering mechanisms (Halsey *et al.*, 1996). Monitoring at Lichfield Cathedral showed that south and west aspects experienced the highest temperatures, rates of temperature change, frequency of heating-cooling cycles and frequency of wetting-drying cycles. From the discussion in Section 4.2.1 it is apparent that physical weathering, caused by fluctuations in temperature and moisture, can theoretically cause weathering of the stone. Therefore, results suggest that physical weathering is more severe on the south and west aspects than the north and east. Furthermore, the survey of sandstone buildings showed that the south and west aspects experienced the greatest amount of blackening (Figure 4.2.13). Black soiling lowers the albedo of the stone and increases the absorption of incident solar radiation (Halsey *et al.*, 1996). Using a scale from zero to one, where zero is the minimum absorption of incident solar radiation and one the maximum, a red sandstone has an absorptivity of around 0.70, while coal fly ash has a value of around 0.95 (Table 6.2.2). It seems reasonable that an increase in the absorption of incident solar radiation will increase the severity of heating-cooling cycles and differential thermal expansion (Halsey *et al.*, 1996). Indeed, Warke *et al.* (1996) showed that soiling with coal and oil fly ash increases surface temperatures, the rate of temperature change and internal temperature gradients. Increased absorption of solar radiation may also increase the number of wetting-drying cycles, and rates of drying. In addition to this, Nord and Tronner (1992) considered that thin black layers on quartz rich sandstones were hydrophobic and noted that they may cause exfoliation. To evaluate this observation, a pillar used to support the balustrade of Birmingham Cathedral was made available from a restoration project.

During the initial stages of restoration the cathedral was cleaned by sandblasting. However, the rear of the balustrade was left with its black soiling, as this was not visible from ground level (Plate 6.2.3). The stone had been exposed to the inner city environment of Birmingham since about 1860. To evaluate the effects of black soiling upon water absorption, a Karsten tube (water absorption tube) was placed on each surface. It was found that black soiling reduced the rate of water absorption from 0.68 l m^{-2} $hour^{-1}$ for unsoiled sandstone, to 0.07 l m^{-2} $hour^{-1}$ (Figure 6.2.1). Paired t-tests showed that the difference between the two surfaces was highly significant ($p<0.01$). This large reduction in water absorption occurred due to the blocking of the pores in the stone, which is easily visible when examining a transverse petrographic thin section of the stone (Plate 6.2.4). Therefore, blackening of stone occurs where initial water absorption is greatest, but ultimately, the trapping of particulate matter reduces water absorption.

Due to the hydrophobic nature of black crusts, any drying of the stone occurs at the most permeable area, enhancing salt concentrations in this area, which in turn leads to localised stone breakdown (Halsey *et al.*, 1996). Further more, differences in water absorption and drying rates cause differences in moisture related behaviour, such as expansion and contraction, which increases shear stresses. This may be one reason why enhanced deterioration is often seen at the edges of ashlar, as the stone-mortar interface may provide a gap in the layer of black soiling (Halsey *et al.*, 1996). Therefore, a local intensification of wetting-drying cycles, wetting-drying rates and salt concentrations occurs due to atmospheric soiling. Furthermore, during low temperatures, freezing may occur, forcing water to expand in a confined space behind the black soiling. This generates further stresses which may enhance deterioration and indeed rapid stone breakdown has been reported following a severe frost (Smith *et al.*, 1994).

From the above discussion it is apparent that atmospheric deposition exerts an important influence on sandstone weathering. A generalised model of the influence of atmospheric deposition upon sandstone weathering has been proposed by Halsey *et al.* (1996) (Figure 6.2.2). Descriptive models of stone deterioration, such as those presented by Bluck and Porter (1991a), Viles (1993), Smith *et al.* (1994) and Halsey *et al.* (1996) provide a useful summary to the series of mechanisms which may cause weathering of stone.

	Mean cover (percent)	Percent of total weathered stone	Percent occurrence in quadrats
Relief	6.0	8.8	83.2
Alveolar	0.1	0.2	2.2
Anthropogenic	4.3	6.4	35.1
Granular Disintegration	4.8	7.0	68.8
Multiple flaking	2.5	3.7	29.7
Multiple scaling	0.5	0.7	6.0
Spalling	5.1	7.4	64.1
Black flaking	4.9	7.2	56.5
Case hardened flaking	1.3	1.9	18.4
Autotrophic flaking	1.1	1.6	17.2
Unaltered flaking	1.3	1.8	19.6
Black scaling	1.8	2.7	29.0
Case hardened scaling	0.2	0.3	3.0
Autotrophic scaling	2.2	3.3	33.1
Unaltered scaling	2.7	3.9	40.4
Black soiling	16.0	23.5	82.2
Case hardened soiling	0.6	0.9	9.5
Autotrophic soiling	12.7	18.7	76.4

Table 6.2.1 Occurrence of sandstone weathering forms on sandstone buildings in the West Midlands.

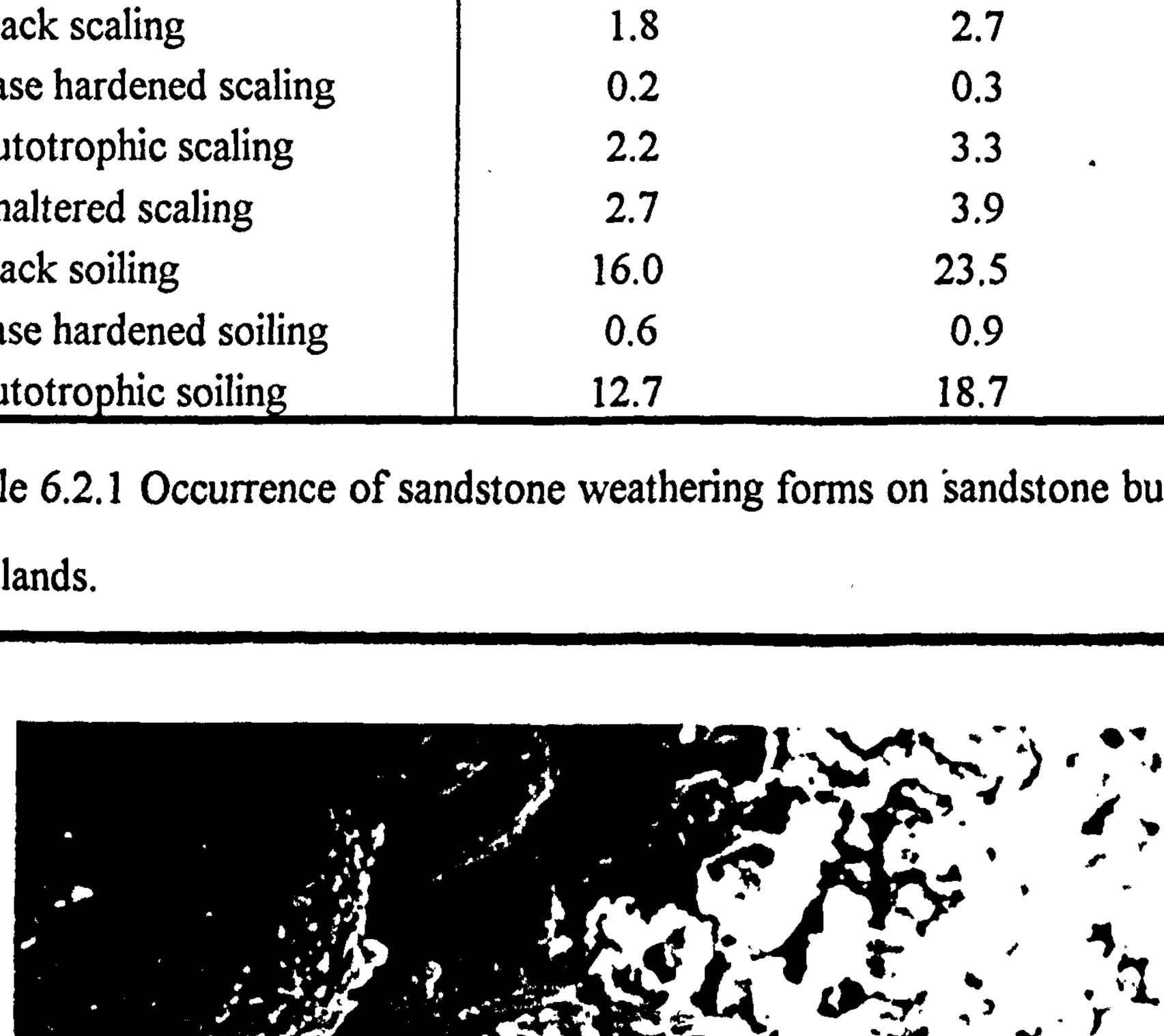

Plate 6.2.1 SEM micrograph of a black scale from Wednesbury, West Midlands. Glassy fly ash particles, varying greatly in size, are the dominant type of fly ash (× 2 500).

Plate 6.2.2 Preferential black soiling on horizontal stones surfaces.

Material	Normal total absorptivity of incident solar radiation
Black non-metallic surface. e.g. asphalt	0.85-0.98 *
Asphalt	0.93
Coal soot	0.95
Red brick, stone or tile.	0.65-0.80 *
Red brick	0.75

Table 6.2.2. Absorptivity of solar radiation for various materials, after Siegel and Howel (1972) and * Threlkeld (1970). Absorptivity is the fraction of the energy incident on a body that is absorbed by the body (Siegel and Howell, 1972).

Plate 6.2.3 Balustrade support from Birmingham Cathedral with Karsten tubes in place.

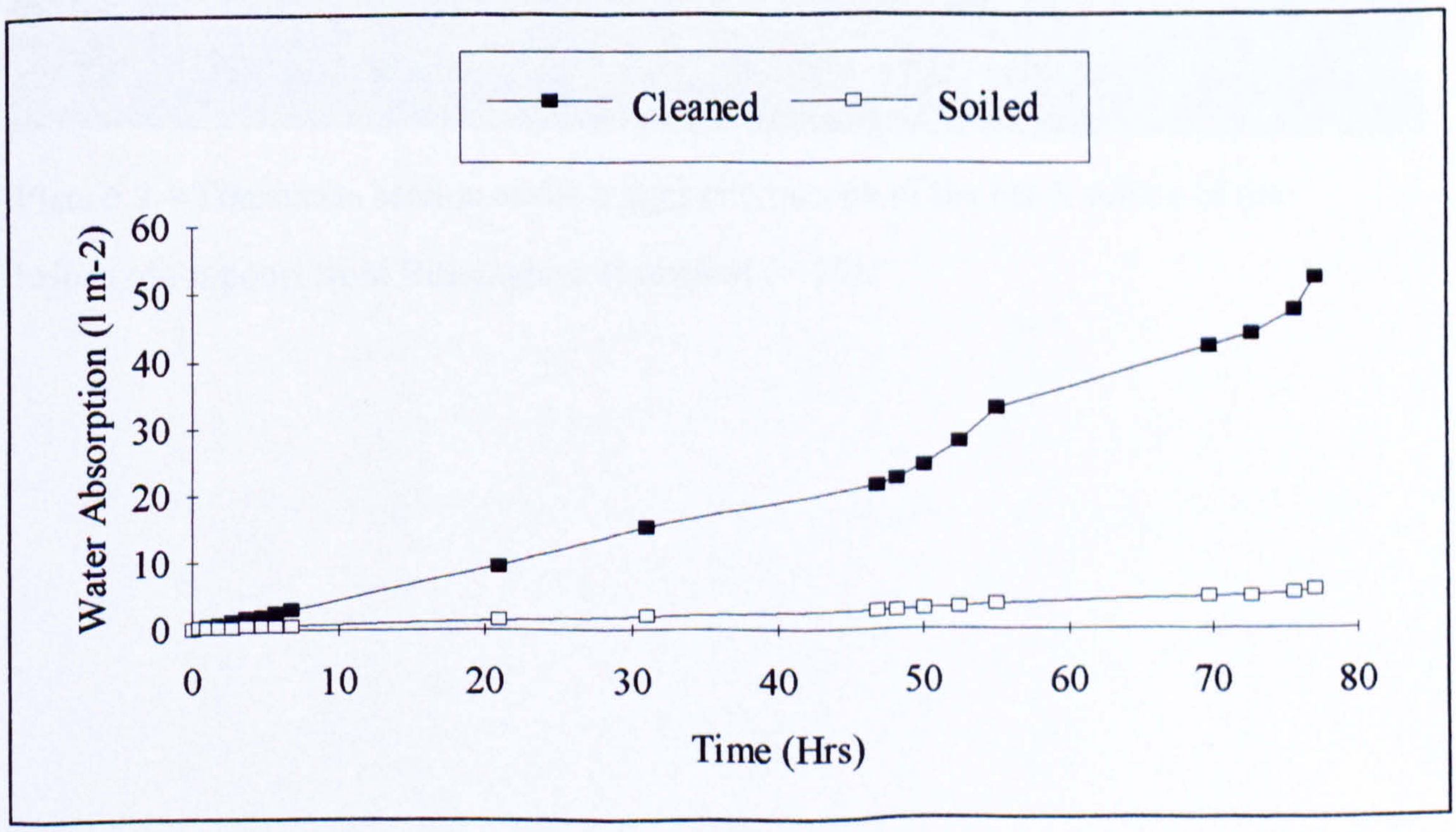

Figure 6.2.1 Water absorption for black soiled and cleaned parts of a sandstone balustrade support from Birmingham Cathedral.

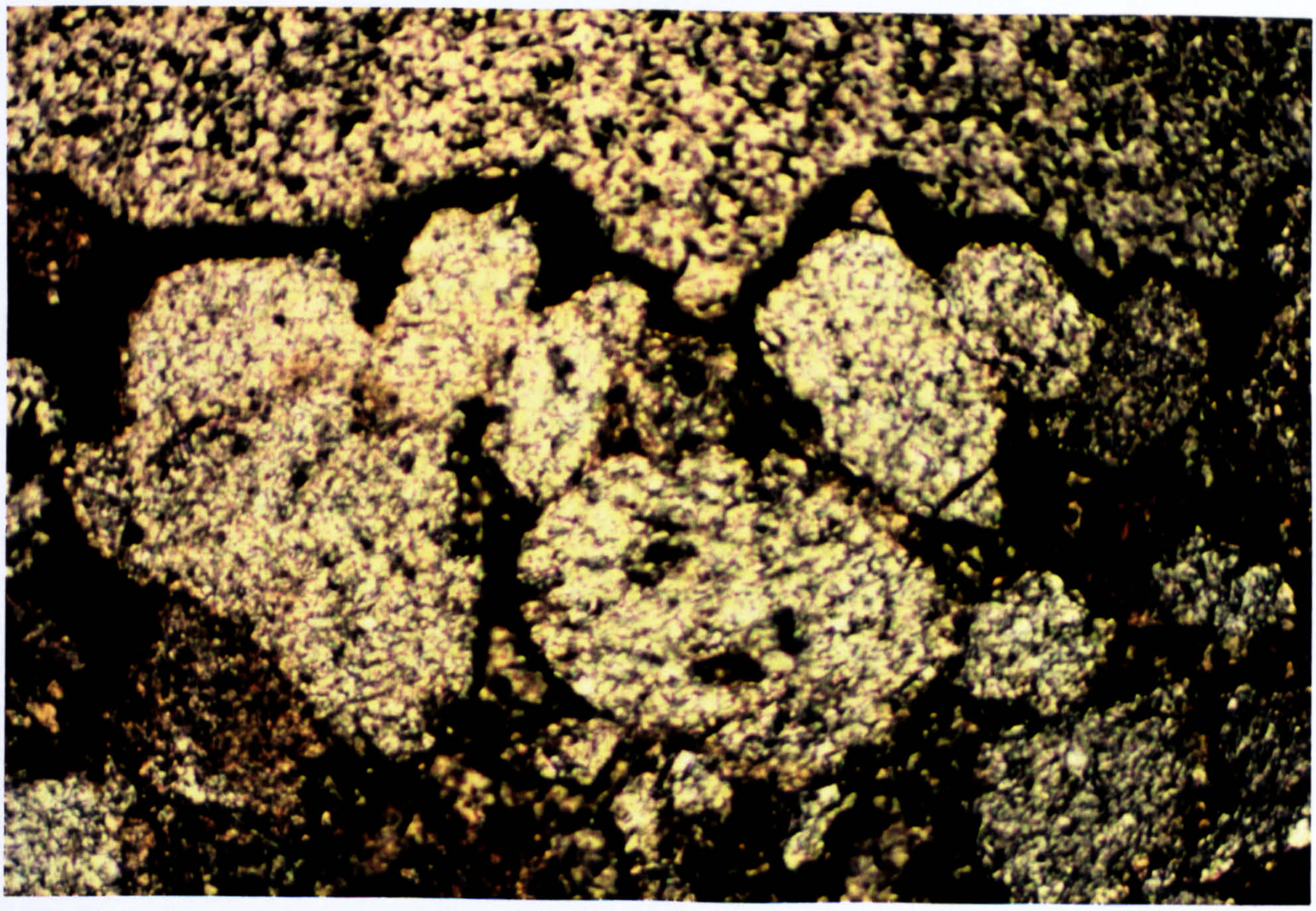

Plate 6.2.4 Transverse section under a light microscope of the black soiling of the balustrade support from Birmingham Cathedral (× 30).

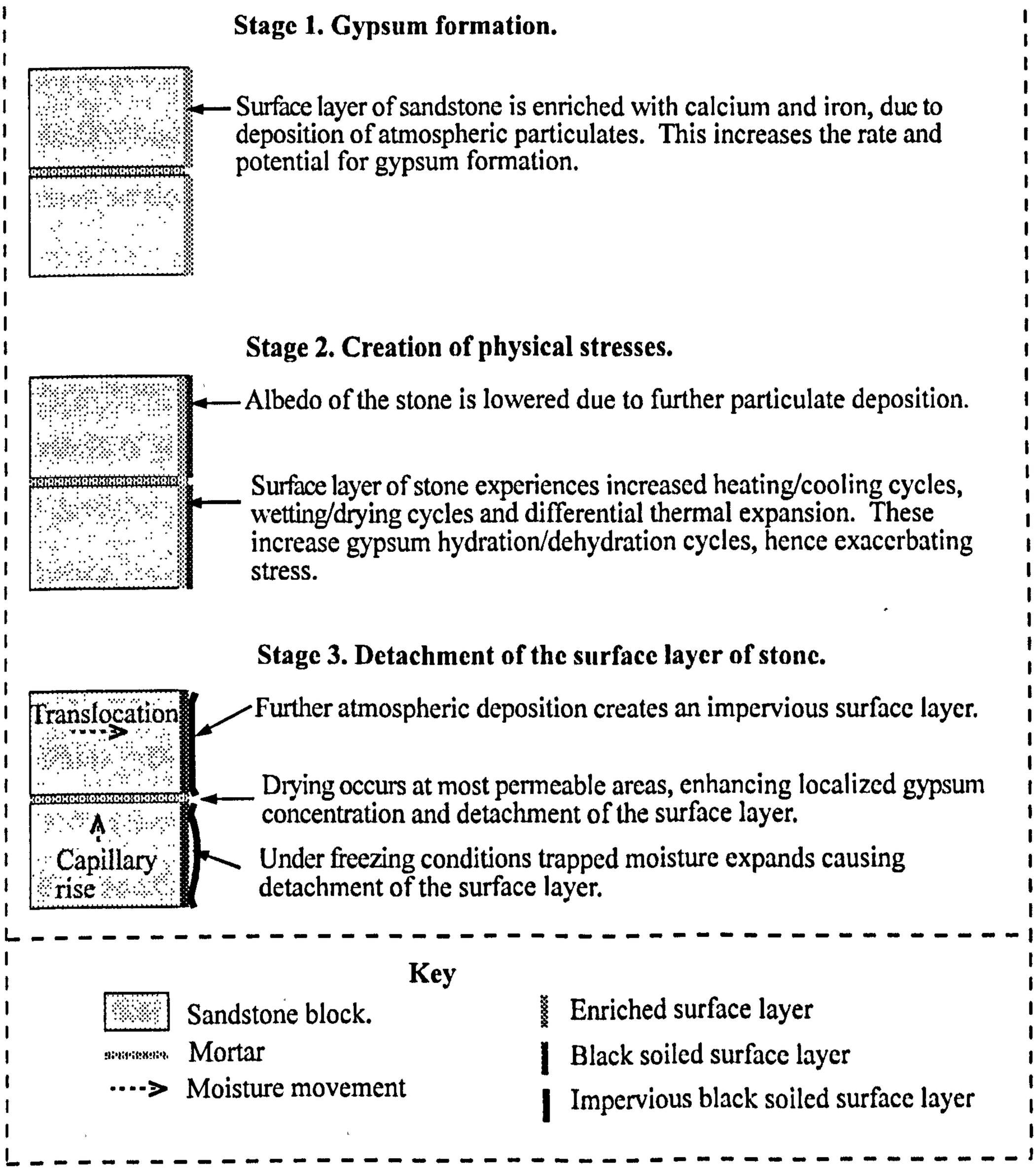

Figure 6.2.2 Generalised three stage model of the breakdown of black soiled sandstone (after, Halsey *et al.*, 1996).

6.3 AUTOTROPHIC SOILING, AUTOTROPHIC FLAKING AND AUTOTROPHIC SCALING

Autotrophic stone was the second most important weathering form in the building survey, being recorded in 78% of the quadrats and accounting for 24% of the total weathering. The building survey showed that autotrophic colonisation was less in urban areas than in rural areas, largely due to atmospheric pollution inhibiting lichen growth (Section 4.2.3). Colonisation of the stone was greatly influenced by the supply of moisture, with greatest colonisation on the north and east aspects, which experienced the most constant supply of moisture (Section 4.2.1).

The building survey showed that stone colonised, by micro-organisms was lost as flakes and scales. The discussion on black flakes and scales suggests that they detach from the stone as a result of physical stresses between the outer layer of the stone and the interior. The outer layer of colonised stone may experience increased physical stresses due to salt weathering, as organic material catalyses gypsum formation. Organic material may also increase freeze-thaw activity, due to increased water retention. Furthermore, organisms exert physical stresses by expanding and contracting, as the organisms hydrate and dehydrate. Due to these mechanisms this layer experiences greater expansion and contraction than the interior of the stone resulting in detachment of flakes and scales. The results showed that autotrophic scaling was much more prevalent than autotrophic flaking. This is the opposite to blackened stone, which experienced greater flaking than scaling. This suggests that the depth of surface alteration may be greater for autotrophic stone, causing scaling to dominate over flaking. This is supported by scanning electron microscopy which shows that organic growth can penetrate into voids in the stone and individual minerals (Plate 6.2.3).

6.4 RELIEF AND ALVEOLAR WEATHERING

Relief weathering occurred widely on sandstone buildings, being recorded for 83% of the quadrats. However, despite this wide occurrence it only accounted for 9% of the total weathered stone. Relief weathering occurs due to inherent differences in parts of the stone, generally visible as certain sedimentary structures, especially bedding planes, weather

faster than others. This may be due to several factors, including a difference in the thermal and moisture properties between sedimentary structures or a difference in the porosity, which may cause different rates of drying, resulting in localised salt crystallisation. During the building survey it was often apparent that sedimentary structures with the greatest rate of weathering contained clays. Certain clay minerals, smectites, may cause deterioration due to swelling and contraction related to the uptake and release of moisture. Furthermore, clays may catalyse gypsum formation (Vendrell-Saz and Garcia-Valles, 1992). Clays may exist in the sandstone before weathering or may form by the breakdown of unstable silicate minerals (Velde, 1992). In this study the formation of clays, due to the hydrolysis of orthoclase feldspar, was suggested by the microcatchment experiment (Section 5.2.2). All of the mechanisms which may cause relief weathering involve temperature or moisture cycles. Monitoring at Lichfield Cathedral has shown that these cycles are greatest on the south and west aspects, the same aspects which experienced the greatest occurrence of relief weathering.

Alveolar were very uncommon on the surveyed buildings, with this weathering form only accounting for 0.2% of the weathered stone and present in only 2.2% of the quadrats. Due to this low occurrence, elucidation of the mechanism responsible for alveolar is difficult. The effects of aspect (Section 4.2.3) do not support the view that wind abrasion creates alveolar. Also, due to the nature of alveolar, no samples of weathered stone could be collected for analysis and therefore the view that salt weathering is responsible for alveolar could not be confirmed.

6.5 GRANULAR DISINTEGRATION AND SPALLING

Granular disintegration and spalling were of similar importance for the weathering of sandstone buildings in the West Midlands. Granular disintegration accounted for 7% of the weathered stone and appeared in 69% of the quadrats, whilst spalling accounted for 7% of the total weathered stone and was present in 64% of the quadrats. The discussion in Section 4.2.2 shows that these weathering forms were most prevalent on the north and east aspects. This is due to slow evaporation that causes salt crystallisation at the surface, whereas, rapid evaporation causes crystallisation to occur in the interior of the stone.

Crystallisation at the surface, results in granular detachment. The crystallisation of salts close to the surface of the stone, causes the heaving of grains. As temperature or moisture availability increases the salts go back into solution. As a result of heaving, the grains at the surface of the stone are surrounded by larger pores, so dry more quickly than the grains that have not been heaved. Consequently, these grains are no longer held by the stone or salt crystals so detach from the surface. Support for this hypothesis is provided by the analysis of weathered samples collected from buildings. Stone affected by granular disintegration has a relatively low sulphate concentration. However, this stone had the highest concentration of soluble chloride of all weathering forms and a very high concentration of soluble nitrate (Table 5.2.14).

Spalling occurred under similar conditions as granular disintegration and had a similar morphology, except that groups of weakly cemented grains detached from the stone. Analysis of weathered stone showed that spalls had the highest soluble nitrate concentration of all weathering forms and a very high soluble chloride concentration. However, the soluble sulphate concentration was relatively low. Results identifying the decisive factors between granular disintegration and spalling are inconclusive. Important factors may include the degree cementation of the stone. This may be related to the original cementation of the stone or secondary cementation, due to the precipitation of solutes upon drying.

6.6 UNALTERED FLAKING AND SCALING

Unaltered scales accounted for only 4% of the total weathered stone, but were present in 40% of the quadrats. They were more common than scales with surface alterations (i.e. black, autotrophic and case hardened scales). The occurrence of unaltered scaling was greatest on the south and west aspects. In Section 4.2.2 it was noted that this may have been due to the greater frequency of temperature and moisture cycles on these aspects. These cycles may contribute to the scaling of the stone directly, but also increase the concentration of salts in the subsurface of the stones. This process results in scaling or flaking as opposed to granular disintegration. Analysis of unaltered scales showed that soluble chloride, nitrate and sulphate concentrations were intermediate between those for

black scaling and autotrophic scaling (Table 5.2.14). The slightly higher salt levels contained in black scaling, suggests that black soiling may increase salt concentrations, as discussed in Section 6.2. The fact that autotrophic scales showed a much lower salt concentration and their greater occurrence on the north and east aspects, suggests that salts are less important for autotrophic scaling. It would therefore seem reasonable that physical mechanisms, imposed by the colonising organisms, as discussed in Section 6.3, are important.

Unaltered flaking was less important than unaltered scaling with it being present in 20% of the quadrats and accounting for 2% of the total weathered stone. It seems reasonable that unaltered flaking results from similar mechanisms as unaltered scaling. However, these mechanisms operate at a reduced depth. The depth of salt crystallisation would be reduced if the stone dried more slowly. Only two sample of unaltered flaking were collected for analysis, but these showed that the flakes had high salt concentrations, especially sulphate. Aspect did not have a marked influence on the occurrence of unaltered flaking. This may be due to the necessity for an intermediate drying rate to cause crystallisation close to the surface, but not close enough to cause granular disintegration.

6.7 MULTIPLE FLAKING AND SCALING

Multiple flaking and scaling combined, accounted for 4% of the total weathered stone and occurred in 34% of the quadrats completed during the building survey. These weathering forms were observed to be most prevalent where a scale or flake had previously detached from the surface. The possibility of multiple flakes and scales representing different depths of wetting seems unlikely, as these different depths would have to occur consistently enough to give defined flakes or scales. An alternative explanation may be that each flake or scale represents the depth of an extreme event, such as a frost, which is then exploited by other weathering mechanisms.

From the discussion on granular disintegration, flaking and scaling, the depth of drying is the key factor in determining the weathering form. This is because the area of drying experiences the greatest concentration of salts. However, as drying takes place the solution

moves towards the drying face and chromatographic separation of solutes and salts may occur. As a result, each salt or solute may have a typical depth of precipitation as the stone dries. These depths may be reasonably consistent giving continuous cycles of crystallisation and precipitation in specific zones. Some of the solutes may have a cementing action on the stone, while salts may cause a zone of disruption. This may result in several distinct flakes or scales forming. Due to the low occurrence of multiple flaking and scaling only one sample of multiple flaking and two of multiple scaling were collected for analysis. Multiple flaking showed intermediate salt concentrations and therefore the chromatographic separation of salts may be responsible for this weathering form (Table 5.2.14). However, the two samples of multiple scaling showed very low salt concentrations and it may be that each scale represents the depth of an extreme frost.

6.8 CASE HARDENED SOILING, CASE HARDENED FLAKING AND CASE HARDENED SCALING

The building survey recorded a low occurrence of case hardened stone, with it accounting for just 3% of the total weathering and occurring in only 25% of the quadrats. Winkler (1987) hypothesised that silica dissolution, followed by precipitation at the surface of the stone, leads to case hardening. However, Winkler (1987) failed to provide analytical results to support this hypothesis. Unfortunately only one sample of case hardened stone was available from the building survey. For this single sample the silica EF Rock was similar to other weathered stone (Table 5.2.6). However, to evaluate Winkler's hypothesis a larger sample is required.

Silica dissolution has traditionally been thought of as a minor factor in sandstone weathering. Laboratory tests show silica, especially quartz, to be poorly soluble under most earth surface conditions. Silica dissolution is influenced by pH with a large increase above pH 9 (Figure 5.2.14). Temperature exerts a lesser influence, with the solubility of quartz doubling from 5 ppm at 20°C to 10 ppm at 40°C (Winkler, 1987). Information such as this is useful when examining the importance of silica dissolution as a weathering mechanism. However, field observations of weathered sandstones, notably by Young and Young

(1992), and Robinson and Williams (1992), suggest that the dissolution of silica may be more important than indicated by these laboratory tests.

The microcatchment experiment has been shown to be capable of monitoring silica dissolution and therefore provides important information on the factors affecting silica dissolution under normal exposure conditions. Results from the microcatchment experiment confirm the importance of pH upon silica dissolution, with some evidence of a positive correlation between the two variables (Table 5.2.1). The acidic nature of the sandstone pore water (Figure 5.2.12) reduces silica dissolution in this study. However, on calcareous sandstones the pore water will have a higher pH, so silica dissolution may become more important. Correlation coefficients provide no evidence of a relationship between temperature or runoff volume and silica dissolution (Table 5.2.1). Statistically, the strongest evidence of an influence on silica dissolution is provided by the positive correlation between silica loss and sulphate loss (Table 5.2.1). The majority of sulphate loss occurs as gypsum and as a result there is some evidence of a positive correlation between silica loss and calcium loss (Table 5.2.1). From field observations, Young (1987), suggested that there may be a general enhancement of silica dissolution under saline conditions. The positive correlation between silica and sulphate loss provides evidence to support this claim, as sulphates were the major salts occurring on the sandstone.

Case hardening was most prevalent on north and east aspects (Section 4.2.2). Monitoring at Lichfield Cathedral shows that these stones experience high, stable moisture contents and low, stable temperatures. This ensures slow drying at the surface of the stone in the same manner to that discussed for granular disintegration. Furthermore, the lower inputs of wind-driven rain, experienced on these aspects, ensure that runoff is minimal and a greater proportion of the moisture results from the capillary rise of ground water. This water may have a higher salt content, which assists silica dissolution. Although case hardening is not a major weathering form it is interesting to note that 62% of stone affected by case hardening is flaking and 10% is scaling. Therefore, if case hardening does occur, detachment of the surface layer is much more likely than for blackened or autotrophic stone. The flaking also showed a different morphology to the black flaking and autotrophic flaking. It occurred as

blistering in a similar way to that reported for limestone by Viles (1993). Case hardening occurs when salts and solutes are deposited in the outer layer of the stone, creating a hardened crust. This crust may continue to build up until the area of the crust exceeds the area of the stone and the crust starts to bow, causing a blister to form. The growth of the crust is presumably the result of slow drying which ensures the deposition of solutes at the surface. The blister continues to grow until it finally bursts, as a result of the stresses created by the difference in area between the crust and the underlying stone. However, bursting of the crust may equally be the result of a catastrophic event, such as a frost or an unusually dry spell that causes very extensive salt crystallisation.

6.9 SUMMARY

From the discussion in Sections 6.2 to 6.8 it is evident that many processes may be involved in sandstone weathering. Indeed, Smith *et al.* (1992) noted that weathering forms are polygenetic, the result of more than one weathering mechanism. These mechanisms operate alongside each other and the relative dominance of each mechanism and the depth at which they operate is a key factor in determining the weathering form. However, the activity of sandstone weathering mechanisms is not linear over time, with alterations taking place, allowing other mechanisms to become important. Initially, most alteration is by chemical and/or biological mechanisms. These alterations provide the means for physical mechanisms to become more effective and consequently cause the loss of stone material. The severity of each mechanism has been shown to be affected by the environmental conditions.

CHAPTER 7

CONCLUSIONS AND FURTHER WORK

The experiments detailed in Chapters 4 and 5 and the synthesis of results in Chapter 6 enable the following conclusions to be drawn concerning the weathering mechanisms and weathering forms affecting sandstone buildings in the West Midlands.

1. On average, total blackened stone accounts for 33% of the total weathering experienced by the buildings. Blackened stone is more prevalent in urban areas, where it may cover more than 40% of the stone, than in rural areas, where it may cover less than 10% of the stone. This contrast is largely the result of atmospheric pollution caused by coal combustion in the 19th century and first half of the 20th century.

2. Blackening of the stone is influenced by environmental conditions, occurring in largest quantities on stones that experience the greatest initial absorption of precipitation. This may be caused by distinct wetting-drying cycles and wind-driven rain. Ultimately the pores of the blackened stone become blocked with particulate matter and absorption is reduced.

3. Detachment of blackened stone, as flaking and scaling, is caused by several mechanisms. The deposition of atmospheric particles increases gypsum concentrations by the direct deposition of gypsum, deposition of calcium and/or catalysing the sulphation of calcium contained in the stone. Blackening lowers the albedo of the stone, increasing rates of heating and consequently thermal stresses. The hydrophobic nature of blackened stone encourages localised stone breakdown, by causing selective areas of drying. These areas experience a greater number of wetting-drying cycles and an increased concentration of salts. Furthermore, the freezing of water trapped behind the black crust may cause detachment.

4. On average, total autotrophic stone accounts for 24% of the total weathering. It is less prevalent in urban areas, where it covers around 11% of the stone, than rural areas, where it covers around 23% of the stone. Atmospheric pollution, inhibiting lichen growth, is responsible for this reduction in urban areas.

5. Environmental conditions influence the autotrophic colonisation of stone, with it occurring in greatest quantities where a relatively constant supply of moisture exists.

6. Autotrophic colonisation of the stone may increase gypsum concentrations and freeze-thaw cycles. However, the dominant mechanism causing the detachment of autotrophic stone is probably the expansion and contraction of organic material, due to wetting-drying cycles.

7. Autotrophic scaling is more prevalent than autotrophic flaking, while black flaking is more prevalent than black scaling. The depth at which weathering mechanisms occur is decisive in the formation of flakes and scales. Autotrophic growth penetrates into the stone, therefore, associated weathering mechanisms occur at depth, causing scaling to be more prevalent than flaking. The opposite occurs for black flaking, as the blackening of the stone is restricted to the surface.

8. Relief weathering accounts for 9% of the total weathering. Several mechanisms may cause relief weathering. However, all of them require temperature and moisture cycles to be active in the stone.

9. Granular disintegration accounts for 7% of the total weathering. It is found in greatest quantities where environmental conditions support slow drying at the surface of the stone. This causes salts to crystallise at the surface, resulting in grains being heaved from the stone.

10. Spalling accounts for 7% of the weathering occurring under similar environmental conditions to granular disintegration. The mechanisms responsible for spalling may be similar to granular disintegration, except that a greater degree of cementation exists between the grains. This may be caused by the original cementing material or created by the precipitation of salts and other solutes.

11. Unaltered scales account for 4% of the total weathered stone. The occurrence of these scales suggest that rapid drying of the stone is necessary for their formation. Rapid drying

causes evaporation to occur in the subsurface of the stone and consequently salts concentrate in this zone. Temperature and moisture cycles, as well as salt weathering mechanisms cause detachment of the scales.

12. Unaltered flakes account for 2% of the total weathered stone. They form under similar environmental conditions as unaltered scales, but may be related to a slightly slower drying rate, causing salts to crystallise closer to the surface of the stone. Consequently, flakes of stone detach as opposed to scales.

13. Multiple flaking and scaling combined account for 4% of the total weathered stone. The mechanisms that cause these weathering forms are not clear. However, it is hypothesised that chromatographic separation of salts and solutes may occur as the stone dries. This results in distinct zones of salt crystallisation, causing disruption of the stone, and zones of solute precipitation, causing cementation of the stone. Consequently, layers of flakes and scales form.

14. Case hardened stone accounts for 3% of the total weathered stone. The occurrence of case hardening shows that it is prevalent on slow drying stone, where runoff is infrequent and the capillary rise of ground water supplies the majority of the moisture. Consequently salt concentrations are high, which increase silicon dissolution. Due to slow drying, silicon precipitates at the surface of the stone causing case hardening.

15. Alveolar account for only 0.2% of the total weathered stone, making it difficult to elucidate the weathering mechanisms responsible. However, no support is provided for the hypothesis that wind abrasion causes alveolar.

16. Weathering forms are polygenetic and the weathering mechanisms that cause them change over time. Initially, most alterations to the stone are chemical and/or biological. These alterations increase the effectiveness of physical weathering mechanisms, which cause the detachment of stone material.

In addition to these conclusions, concerning the weathering mechanisms and weathering forms affecting sandstone buildings in the West Midlands, the following ideas require further research.

1. Improvements in the chemical analysis of exposure trial samples are required. Also, a method of exposing small samples under conditions more similar to those found on buildings would improve the extrapolation of results obtained with exposure trials to the weathering of buildings.

2. The depth of drying has been suggested as a critical factor in determining which weathering forms develop. Techniques capable of monitoring moisture gradients at the millimetre scale are required to quantify the importance of this factor.

3. The microcatchment experiment has shown that silicon is soluble under the environmental conditions studied, but suggests that it may be more soluble for calcareous sandstones and under more saline conditions. To test these hypotheses further research is required.

4. Hydrolysis of orthoclase to kaolonite has been shown to cause weakening of the stone. The hypothesis that smectites may form in calcareous sandstones needs further attention, as the swelling characteristics of these clays may be important in the weathering of these stones.

5. The influence of superficial weathering upon the effectiveness of thermal and moisture cycles requires further research. Recently, an initial investigation on the effects of black soiling upon thermal responses has been conducted by Warke *et al.* (1996). Similar work could be undertaken for other weathering forms.

6. The formation of multiple flaking and multiple scaling lacks explanation and the hypothesis that chromatographic separation of salts and solutes is responsible, requires further work.

7. The mechanisms responsible for the formation of alveolar require further investigation. A survey of the occurrence of alveolar on a rock type where they are more prevalent would allow the environmental conditions and weathering mechanisms responsible for their formation to be elucidated.

8. The effects on weathering of a wider range of environmental conditions, than experienced in the West Midlands, could be obtained by conducting a more widespread building survey.

APPENDIX 1

A SUMMARY OF STATISTICAL TECHNIQUES USED

A1.1 DESCRIPTIVE STATISTICS

Descriptive statistics are calculated separately for each variable, and they provide such basic information as the mean, minimum and maximum values, different measures of variation, as well as data about the shape of the distribution of the variable.

The mean is a particularly informative measure of central tendency, especially if it is reported along with its confidence intervals. Usually we are interested in the extent to which the sample is informative about the population. The larger the sample size, the more reliable its mean. The larger the variation of data values, the less reliable the mean. Standard deviation is a commonly used measure of variation and is favoured because it is reported in the same units as the original data. The shape of a variable's distribution, is created by the frequency of values for different ranges of the variable. Typically, the distribution is examined to see if it is normally distribution. Simple descriptive statistics can provide some information relevant to this issue. For example, if the skewness (which measures the deviation of the distribution from symmetry) is clearly different from 0, then the distribution is asymmetrical, while normal distributions are perfectly symmetrical. If the kurtosis (which measures peakedness of the distribution) is clearly different from 0, then the distribution is either flatter or more peaked than normal; the kurtosis of the normal distribution is 0. More precise information can be obtained by performing a test of normality to determine the probability that the sample came from a normally distributed population. Alternatively, the data can be visually examined using a histogram with the normal curve superimposed over the top. This also allows examination of various aspects of the distribution qualitatively. For example, the distribution could be bimodal (have 2 peaks) suggesting that the sample came from two different populations.

A1.2 CORRELATION

The correlation coefficient (Pearson r) is a measure of the linear relationship between two or more variables. Its values range from -1.00 to +1.00, where -1.00 represents a perfect negative correlation, while a value of +1.00 represents a perfect positive correlation. A value of 0.00 represents a lack of correlation. This test assumes that the sample came from a normally distributed population.

A1.3 T-TESTS FOR INDEPENDENT AND DEPENDENT SAMPLES

The t-test is the most commonly used method to evaluate the difference in means between two groups. The p-level reported with a t-test represents the probability of error involved in rejecting the null hypothesis and excepting the alternative hypothesis which is the existence of a difference between means. Theoretically, the t-test can be used even if the sample sizes are very small (e.g., as small as 10), as long as the variables are normally distributed and the variation in the two groups is not reliably different. The equality of variances assumption can be verified with Levene's test. If Levene's test generates a significant F ($P<0.05$) then the assumption has been violated and the t-test assuming unequal variance should be used. The normality assumption can be evaluated by looking at the distribution of the data or by performing a normality test. Several normality tests exist, but in this research the Shapiro-Wilks W test is used as it is the preferred test in many statistics texts. If the W statistic is significant ($p<0.05$), then the hypothesis that the distribution is normal should be rejected. It is common not to have enough data to carry out a normality test. If this is the case then visual examination of the data with a histogram may enable the distribution to be considered normal. If the distribution is not normal the data may be transformed or alternatively one of the nonparametric alternatives to the t-test can be used (see Section A1.6) (Stuttard, 1994).

A separate t-test is used for dependent samples which takes advantage of an important source of within-group variation that can be easily identified and excluded from the analysis. If two groups of observations (that are to be compared) are based on the same sample of subjects which were tested twice (e.g., before and after a treatment), then part of the within-group variation in both groups of scores can be attributed to the initial differences between subjects. So whenever there is a natural pairing of data this test is favoured as it produces better results than the t-test for independent samples. The theoretical assumptions of the t-test for independent samples also apply to the dependent samples test. If these assumptions are clearly not met, then one of the nonparametric tests should be used.

A1.4 ANALYSIS OF VARIANCE (ANOVA)

As with the t-test the purpose of ANOVA is to test differences in means for statistical significance. This is accomplished by partitioning the total variance into the component that is due to random error (i.e., within-group SS) and the components that are due to differences between groups. These latter variance components are then tested for statistical significance, and, if significant, the null hypothesis is rejected, and the alternative hypothesis that the means are different from each other is accepted. If only two means are being compared, then ANOVA will give the same results as the t-test. The within-group SS is usually referred to as Error variance denoting that it cannot be accounted for. Whereas the between group, or SS Effect variance, is due to the differences in means between the groups.

ANOVA is a flexible and powerful technique that can be applied to complex research issues. In a typical experiment, many factors are taken into account. One important reason for using ANOVA methods rather than multiple two-group studies analysed via t-tests is that the former method is more efficient, and with fewer observations can supply more information. With ANOVA each factor is tested while controlling for all others. Further more, ANOVA allows the detection of interaction effects between variables, and, therefore, to test more complex hypotheses about reality. Sometimes effects are found that are not expected and in these cases post hoc procedures are used to test their statistical significance. Several post hoc tests exist with different degrees of conservativness. In this research Tukey's HSD (honest significant difference) is used as it demonstrates an intermediate amount of conservativness and has two forms; one for unequal sample sizes and another for equal sample sizes.

As with the t-test ANOVA is based on various assumptions. It is assumed that the dependent variable is normally distributed within groups. However, the F test is remarkably robust to deviations from normality. If the kurtosis is greater than 0, then the F tends to be too small and we cannot reject the null hypothesis even though it may be incorrect. The opposite is the case when the kurtosis is less than 0. The skewness of the distribution usually does not have a sizeable effect on the F statistic. If the n per cell is fairly large, then

deviations from normality do not matter much because of the central limit theorem. As with the t-test it is assumed that the variances in the different groups of the design are equal; this assumption is called the homogeneity of variances assumption. However, the F statistic is quite robust against violations of this assumption. However, one instance when the F statistic is very misleading is when the means are correlated with variances across cells of the design. The reason this is a dangerous violation is if there is a high mean in the one cell which also has a large variance the mean is quite unreliable, as indicated by the large variance. However, because the overall F statistic is based on a pooled within-cell variance estimate, the high mean is identified as significantly different from the others, when in fact it is not if one based the test on the within-cell variance in that cell alone.

A1.5 CLUSTER ANALYSIS

The term cluster analysis encompasses a number of different classification algorithms which are used to organise observed data into meaningful structures. In this research cluster analysis started with hierarchical methods in order to identify the number of clusters and highlight relationships between them. Agglomerative hierarchical techniques (tree clustering) join objects into successively larger clusters, using some measure of similarity or distance. A typical result of this type of clustering is the hierarchical tree or dendrogram. Along the bottom of the dendrogram each object is in a class by itself, in very small steps the criteria is relaxed as to what is and is not unique. As a result more and more objects link together into larger and larger clusters of increasingly dissimilar elements. Finally, in the last step, all objects are joined. In these plots, the vertical axis denotes the linkage distance. Thus, for each node in the graph the criterion distance at which the respective elements were linked together into a new single cluster can be read off. As the result of a successful analysis, clusters can be detected.

Hierarchical methods use the distances between objects to form clusters. These distances can be based on a single dimension or multiple dimensions. The most straightforward and probably the most common multi-dimensional measure is Euclidean distances. This is the measure used in this research and it is simply the geometric distance in multidimensional space. However, other distance measures exist which allow weightings to be added under

certain conditions. At the first step, when each object represents its own cluster, the distances between those objects are defined by the Euclidean distance. However, once several objects are linked together, a linkage or amalgamation rule is needed to determine when two clusters are sufficiently similar to be linked together. In this research three conceptual different amalgamation rules were used to enable real structure in the data to be more conclusively identified (Howard, 1991). The rules were: The unweighted arithmetic averaging technique, as it does not impose a structure on the data; The single linkage method, as it is good at finding long straggling clusters, but susceptible to noise points (Everitt 1980), causing an artificial loss of clusters; Ward's method which uses an ANOVA approach to evaluate the distance between clusters.

Hierarchical clustering techniques can sacrifice group composition so a k-means cluster analysis was also carried out to check the composition of clusters once the number of clusters had been identified with the hierarchical methods. K-means clustering is very different from the hierarchical methods. It allows computation of the required number (k) of clusters of greatest possible distinction. It starts with k random clusters, and then moves objects between those clusters with the goal to minimise variability within clusters and maximise variability between clusters. This is analogous to ANOVA in reverse. Usually, as the result of a k-means cluster analysis the means for each cluster are examined to assess how distinct the clusters are. Ideally very different means would be obtained. The magnitude of the F values from the analysis of variance performed on each dimension is another indication of how well the respective dimension discriminates between clusters. Cluster analysis is not a typical statistical test, cluster analysis methods are mostly used when a priori hypotheses does not exist, but exploration of the data is required. Therefore, hypothesis testing is really not appropriate here, even though p-levels are reported to indicate if clusters are distinct from each other.

A1.6 NONPARAMETRIC STATISTICS

Nonparametric statistics are less statistically powerful (sensitive) than their parametric counterparts. However, parametric methods, such as ANOVA, are based on assumptions, which if violated may give incorrect results. For many variables of interest, it is not known

for sure that the population is normally distributed. Another factor that often limits the applicability of tests based on the assumption that the sampling distribution is normal is the size of the sample. It can be assumed that the sampling distribution is normal even if we are not sure that the distribution of the variable in the population is normal, as long as the sample is large enough (e.g., 100 or more observations). However, if the sample is very small, then parametric tests can only be used if it is certain that the variable is normally distributed, and it may be hard to test this assumption for very small samples. Therefore, nonparametric methods are most appropriate when the sample sizes are small. There is at least one nonparametric equivalent for each parametric type of test.

Usually, when two samples are compared concerning their mean, the t-test for independent samples is used; nonparametric alternatives for this test are the Wald-Wolfowitz runs test, the Mann-Whitney U test, and the Kolmogorov-Smirnov two-sample test. If there are multiple groups ANOVA is replaced by the nonparametric equivalents, the Kruskal-Wallis analysis of ranks and the Median test. If two variables measured in the same sample are to be compared the t-test for dependent samples would be used. Nonparametric alternatives to this test are the Sign test and Wilcoxon's matched pairs test. If there are more than two variables that were measured in the same sample, then ANOVA with replication is used. A nonparametric alternative to this method is Friedman's two-way analysis of variance.

To express a linear relationship between two variables one usually computes the Pearson correlation coefficient. A nonparametric equivalent is Spearman R. This is similar to the Pearson correlation coefficient, except that it is computed from ranks.

APPENDIX 2

REPEATABILITY OF THE BUILDING SURVEY

In order to assess the repeatability of the building survey, one of the first buildings to be surveyed was re-surveyed at the end of the study (Table A2.1). The results showed that the mean percentage cover of each weathering form was generally very close to that obtained during the first survey (Table A2.2). However, paired t-tests showed that for six of the weathering forms evidence exists to suggest that the results differed between the two surveys. These six weathering forms generally had a low occurrence, suggesting that the accuracy of recording weathering forms with a sparse cover may not be adequate. These six weathering forms were re-surveyed on another three buildings. The results from these buildings suggest that these six weathering forms were repeatable after a few buildings had been surveyed and therefore a learning curve may exist (Table A2.2). The slight lack of repeatability for some weathering forms for the first few buildings to be surveyed does not present a problem in this research. Repeatability was achieved for the majority of weathering forms, and certainly all the major ones. The order with which the buildings were surveyed was random within the study area, therefore regional differences were not created due to this learning curve. When examining factors, such as aspect, repeatability is not a serious consideration as data for each aspect was obtained from each building, hence equalising out any errors.

Survey	Survey dates			
	E2	E5	E7	E9
First	21.6.94	19.7.94	3.8.94	25.10.94
Second	6.12.94	8.12.94	8.12.94	8.12.94

Table A2.1 Dates of surveying and re-surveying of the four buildings used to assess the repeatability of the building survey technique.

Weathering forms	Survey	E2 Mean	E2 p-value	E5 Mean	E5 p-value	E7 Mean	E7 p-value	E9 Mean	E9 p-value
Relief	First	**7.0**	**0.0002**	6.5	0.1062	5	0.1350	7.3	0.5195
	Second	**10.8**		7.7		5.8		6.9	
Alveolar	First	0.1	0.4229						
	Second	0.0							
Anthropogenic	First	**0.0**	**0.0002**	5.3	0.3030	1.1	0.1677	7.7	0.5478
	Second	**2.1**		5.9		0.6		6.7	
Gran. dis.	First	***4.7***	***0.0236***	3.4	0.1017	3.4	0.9742	4.5	0.1519
	Second	***6.4***		4.2		3.4		3.6	
Multiple flaking	First	***4.3***	***0.0440***	**1.2**	**0.0001**	1.6	0.8992	1.5	0.2805
	Second	***1.8***		**3.2**		1.5		2.2	
Multiple scaling	First	0.3	0.7076						
	Second	0.2							
Spalling	First	5.8	0.6167						
	Second	6.3							
Black flaking	First	5.2	0.1975						
	Second	3.9							
Case hard. flak.	First	**3.6**	**0.0244**	0.1	0.3024	0.0	NA	0.1	0.1794
	Second	**1.3**		0.0		0.0		0.4	
Autotrophic flak.	First	1.4	0.7586						
	Second	1.3							
Unaltered flaking	First	1.8	0.1825						
	Second	0.9							
Black scaling	First	1.2	0.2863						
	Second	1.9							
Case hard. scal.	First	0.1	0.2544						
	Second	0.0							
Autotrophic scal.	First	2.4	0.5828						
	Second	2.1							
Unaltered scaling	First	3.1	0.7666						
	Second	3.3							
Black soiling	First	7.9	0.2135						
	Second	9.7							
Case hard. soil.	First	**0.0**	**0.0016**	**0.1**	**0.0001**	0.4	0.0820	4.6	0.5070
	Second	**0.6**		**1.4**		1.0		3.5	
Autotrophic soil.	First	15.1	0.8201						
	Second	15.6							

Table A2.2 Comparison of the results from two surveys of building E2 and partial re-surveys of buildings E5, E7 and E9. For figures in bold there is strong evidence of a difference between the two surveys and figures in bold italics suggest some evidence of a difference betwen the two surveys.

APPENDIX 3

BUILDING SURVEY DATA

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
C1N1	0.2-1.2	3	13.50	15	0	0	15	0	0	15	5	0	5	5	0	0	0	0	5	0	5
C1N2	0.2-1.2	3	12.00	5	0	0	10	5	0	10	5	5	15	0	0	0	0	0	5	5	15
C1N3	0.2-1.2	3	12.00	5	0	0	5	0	0	10	5	5	5	5	5	0	0	0	5	0	10
C1N4	0.2-1.2	3	12.00	5	0	15	10	0	0	5	10	5	0	5	0	0	0	0	5	5	5
C1N5	1.2-2.2	3	12.00	0	0	0	10	0	0	5	10	0	0	5	0	0	0	0	15	0	5
C1N6	0.2-1.2	3	12.00	0	0	0	5	0	0	5	10	5	0	0	0	0	0	0	20	0	5
C1N7	1.2-2.2	3	12.00	5	0	0	5	0	0	5	10	0	0	5	0	0	0	5	15	0	5
C1N8	0.2-1.2	3	12.00	5	0	0	10	0	0	5	10	5	0	5	0	0	0	0	10	5	5
C1N9	1.2-2.2	3	12.00	0	0	0	5	0	0	5	10	0	0	0	0	0	5	0	15	0	10
C1N10	0.2-1.2	3	18.00	0	0	0	10	0	0	5	10	0	5	0	0	0	5	0	20	0	5
C1N11	0.2-1.2	3	18.00	5	0	0	10	5	0	10	5	0	0	0	5	0	5	5	10	5	5
C1N12	0.2-1.2	3	18.00	0	0	0	5	0	0	5	15	5	5	0	5	0	0	0	20	5	15
C1N13	1.2-2.2	3	18.00	0	0	0	5	0	0	10	10	0	0	5	0	0	5	5	15	0	20
C1N14	0.2-1.2	3	13.50	5	0	0	5	5	0	5	15	0	5	0	10	0	0	0	20	0	10
C1N15	1.2-2.2	3	13.50	0	0	0	10	0	0	10	10	0	5	0	0	0	10	5	15	0	10
C1E1	0.2-1.2	95	15.19	5	0	0	5	5	0	5	20	0	0	0	10	0	0	0	20	0	0
C1E2	1.2-2.2	95	15.19	5	0	0	10	5	0	10	15	0	0	0	0	0	0	0	15	0	5
C1E3	0.2-1.2	95	15.19	10	0	0	10	5	0	10	15	0	0	0	0	0	0	10	15	0	0
C1E4	1.2-2.2	95	15.19	5	0	0	10	5	0	10	10	5	0	0	0	0	5	5	15	5	5
C1E5	0.2-1.2	95	3.38	10	5	0	5	0	0	5	10	0	0	5	5	0	0	0	15	5	0
C1E6	1.2-2.2	95	6.75	0	0	0	5	0	0	10	10	0	0	0	0	0	0	10	10	0	5
C1E7	0.2-1.2	95	3.38	5	0	0	5	0	0	5	10	0	0	0	10	0	0	0	20	0	0
C1E8	1.2-2.2	95	6.75	5	0	0	5	0	0	5	10	0	0	0	0	0	0	10	10	0	0
C1E9	0.2-1.2	95	6.75	5	5	0	10	0	0	10	15	5	0	0	5	0	0	5	15	0	0
C1E10	1.2-2.2	95	6.75	0	0	0	5	0	5	10	5	0	0	0	5	0	0	5	10	0	5
C1E11	0.2-1.2	95	10.13	10	0	0	10	0	0	10	10	0	0	0	5	0	5	5	10	0	5
C1S1	0.2-1.2	185	27.00	5	0	0	5	0	0	5	25	10	0	5	0	0	0	0	30	5	5
C1S2	1.2-2.2	185	27.00	10	0	0	10	0	5	5	25	0	0	0	0	0	0	15	25	0	0
C1S3	0.2-1.2	185	27.00	15	0	0	0	0	0	5	25	5	0	5	0	0	0	0	30	0	0
C1S4	1.2-2.2	185	27.00	0	0	0	5	0	0	5	30	0	0	0	0	0	0	10	30	0	5
C1S5	0.2-1.2	185	40.50	0	0	0	10	5	0	15	15	5	0	0	0	0	0	0	15	5	5
C1S6	1.2-2.2	185	40.50	0	0	0	5	10	0	25	20	0	0	0	5	5	0	5	15	0	0
C1S7	0.2-1.2	185	40.50	5	0	0	5	0	5	15	10	0	0	0	5	0	0	10	10	0	0
C1S8	0.2-1.2	185	30.38	5	5	0	5	5	0	5	20	0	0	0	5	0	0	0	25	0	5
C1S9	1.2-2.2	185	30.38	0	0	0	5	5	5	10	10	0	0	0	5	0	0	5	10	0	5
C1S10	0.2-1.2	185	6.75	5	0	0	5	0	0	10	10	5	5	0	0	0	0	0	15	5	10
C1S11	1.2-2.2	185	6.75	5	0	0	5	0	0	5	15	0	0	0	5	0	0	10	20	0	0
C1S12	0.2-1.2	185	6.75	10	0	0	10	0	0	5	15	0	0	0	0	0	0	0	15	0	10
C1S13	1.2-2.2	185	6.75	5	0	0	5	0	0	0	25	0	0	0	5	0	0	5	30	0	0
C1W1	0.2-1.2	273	8.55	10	0	0	5	0	0	5	5	0	0	0	0	0	5	5	10	0	15
C1W2	1.2-2.2	273	8.55	5	0	0	5	0	0	5	15	0	0	0	0	0	0	0	20	0	0
C1W3	0.2-1.2	273	8.55	0	0	0	5	0	0	5	10	0	0	0	10	0	0	0	40	0	0
C1W4	1.2-2.2	273	8.55	5	0	0	0	0	0	5	20	0	0	0	0	0	0	0	30	0	5
C1W5	0.2-1.2	273	8.55	5	0	0	5	0	0	5	40	0	0	5	0	0	0	0	30	0	0
C1W6	1.2-2.2	273	8.55	5	0	0	0	0	0	5	10	0	0	0	0	0	0	5	10	0	5
C1W7	0.2-1.2	273	8.55	10	0	0	5	0	0	5	20	0	0	0	0	0	0	0	30	0	0
C1W8	1.2-2.2	273	8.55	5	0	0	5	0	0	0	20	0	0	5	0	0	0	0	30	0	5
C1W9	0.2-1.2	273	8.55	0	0	0	5	0	0	5	20	5	0	5	5	0	0	0	35	0	5
C1W10	1.2-2.2	273	8.55	5	0	0	5	0	0	5	10	0	0	5	0	0	5	5	15	0	10
C1W11	0.2-1.2	273	6.41	0	0	0	5	0	0	15	5	5	0	0	5	0	0	5	10	0	0
C2N1	0.2-1.2	10	8.10	5	0	5	5	0	0	5	0	0	0	0	5	0	5	5	10	0	40
C2N2	1.2-2.2	10	8.10	0	0	5	5	0	0	5	0	0	0	0	0	0	0	0	5	0	40
C2N3	0.2-1.2	10	5.40	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	10	0	20
C2N4	1.2-2.2	10	5.40	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	20
C2S1	0.2-1.2	187	18.00	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	20
C2S2	1.2-2.2	187	18.00	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	5
C2S3	0.2-1.2	187	18.00	10	0	5	0	0	0	0	5	0	0	0	0	0	0	0	25	0	15
C2S4	1.2-2.2	187	18.00	10	0	5	0	0	0	5	0	0	0	0	0	0	0	0	20	0	15
C2W1	0.2-1.2	281	11.25	5	0	5	5	0	0	5	5	0	0	0	0	0	0	0	10	0	10
C2W2	1.2-2.2	281	11.25	5	0	5	5	0	0	0	0	0	0	0	0	0	0	5	20	0	5
C2W3	0.2-1.2	281	11.25	10	0	5	5	0	0	5	0	0	0	0	0	0	0	0	25	0	5
C2W4	1.2-2.2	281	11.25	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	10
C3N1	0.2-1.2	5	7.20	10	0	0	5	0	0	10	5	0	0	0	0	0	0	0	20	0	0
C3N2	1.2-2.2	5	7.20	10	0	0	5	0	0	0	5	0	0	0	5	0	0	0	75	0	5
C3N3	0.2-1.2	5	36.00	5	0	0	5	0	0	5	20	10	5	0	0	0	0	0	35	0	10
C3N4	0.2-1.2	5	36.00	5	0	0	5	0	0	5	15	5	0	0	0	0	0	0	40	5	5
C3N5	1.2-2.2	5	36.00	10	0	0	5	0	0	0	0	0	0	0	5	0	5	5	15	0	10
C3N6	0.2-1.2	5	18.00	5	0	0	10	0	0	10	20	0	10	0	0	0	0	0	30	10	10
C3N7	0.2-1.2	5	18.00	5	0	5	15	5	0	10	25	5	5	0	0	0	0	0	20	5	5
C3N8	1.2-2.2	5	18.00	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	15	0	5
C3N9	0.2-1.2	5	14.40	0	0	0	10	0	0	10	20	5	5	0	0	0	0	0	30	5	10
C3N10	0.2-1.2	5	7.20	10	0	0	5	5	0	10	5	0	0	0	0	0	0	5	35	0	0
C3N11	1.2-2.2	5	7.20	5	0	0	0	5	0	10	0	0	0	0	5	0	0	5	10	0	0
C3E1	0.2-1.2	96	6.00	5	0	0	10	0	0	5	0	0	0	5	0	0	0	10	5	0	10

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
C3E2	1.2-2.2	96	6.00	5	0	0	5	0	0	5	0	0	0	5	0	0	0	5	10	0	0
C3E3	0.2-1.2	96	9.00	5	0	0	5	0	0	0	0	0	0	0	5	0	0	5	10	0	5
C3E4	1.2-2.2	96	9.00	10	0	0	5	0	0	0	0	0	0	0	5	0	10	0	5	0	40
C3E5	0.2-1.2	96	3.00	15	0	0	10	0	0	0	5	0	0	0	0	0	0	5	50	0	0
C3E6	1.2-2.2	96	6.00	5	0	5	5	0	0	0	5	0	0	0	0	0	0	0	70	0	0
C3E7	0.2-1.2	96	6.00	0	0	0	5	0	0	0	0	0	0	0	5	0	10	5	15	0	40
C3E8	1.2-2.2	96	9.00	5	0	0	0	0	0	0	0	0	0	0	0	0	5	0	10	0	70
C3E9	0.2-1.2	96	12.00	10	0	0	5	0	0	5	0	0	0	0	5	0	5	5	15	0	25
C3E10	1.2-2.2	96	12.00	5	0	0	5	0	0	5	0	0	0	0	0	0	0	5	15	0	5
C3E11	0.2-1.2	96	9.00	5	0	10	0	5	0	10	0	0	0	0	5	0	10	5	20	0	40
C3E12	1.2-2.2	96	9.00	5	0	0	0	0	0	0	0	0	0	0	5	0	5	0	10	0	75
C3S1	0.2-1.2	188	6.00	5	0	0	0	0	0	5	0	0	0	0	5	0	0	10	15	0	5
C3S2	1.2-2.2	188	12.00	5	0	0	0	0	0	5	0	0	0	0	5	0	0	10	5	0	0
C3S3	0.2-1.2	188	6.00	5	0	0	10	0	0	5	0	0	0	0	5	0	0	15	30	0	0
C3S4	1.2-2.2	188	6.00	10	0	25	0	0	0	0	0	0	0	0	5	0	5	5	15	0	20
C3S5	0.2-1.2	188	12.00	5	5	0	5	0	0	5	0	0	0	0	5	0	0	10	10	0	5
C3S6	1.2-2.2	188	12.00	5	0	10	0	0	0	5	0	0	0	0	10	0	0	5	25	0	5
C3S7	0.2-1.2	188	6.00	5	0	0	5	10	0	10	0	0	0	0	5	0	10	10	5	0	5
C3S8	1.2-2.2	188	12.00	10	0	5	5	0	0	10	0	0	0	0	5	0	5	5	10	0	10
C3S9	0.2-1.2	188	18.00	10	0	0	0	0	0	10	10	0	0	0	0	0	0	0	50	0	0
C3S10	1.2-2.2	188	18.00	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	90	0	5
C3W1	0.2-1.2	276	5.00	15	0	10	5	0	0	0	15	0	0	0	25	0	5	5	10	0	5
C3W2	1.2-2.2	276	5.00	10	0	25	0	0	0	5	0	0	0	0	10	0	0	0	30	0	5
C3W3	0.2-1.2	276	15.00	10	0	5	5	0	5	5	0	0	0	0	15	0	0	0	50	0	0
C3W4	1.2-2.2	276	20.00	5	0	10	0	0	0	5	0	0	0	0	10	0	0	0	60	0	0
C3W5	0.2-1.2	276	15.00	10	0	5	5	0	0	10	15	0	0	0	5	0	0	5	20	0	0
C3W6	0.2-1.2	276	10.00	5	0	0	5	5	0	10	0	0	0	0	10	0	5	15	20	0	0
C3W7	1.2-2.2	276	10.00	15	0	0	5	0	0	5	0	0	0	0	10	0	0	10	5	0	0
C4N1	0.2-1.2	2	9.00	5	0	0	5	5	0	5	5	0	0	0	5	0	0	5	5	0	5
C4N2	1.2-2.2	2	12.00	5	0	5	5	0	0	5	5	0	0	0	0	0	0	5	15	0	5
C4N3	0.2-1.2	2	9.00	5	0	5	5	0	0	5	5	0	5	0	0	0	5	0	10	10	20
C4N4	1.2-2.2	2	12.00	5	0	5	5	0	0	5	0	0	0	0	5	0	0	5	10	0	5
C4N5	0.2-1.2	2	9.00	5	0	0	10	0	0	10	10	5	0	0	0	0	0	0	20	5	5
C4N6	1.2-2.2	2	12.00	5	0	5	10	0	0	5	0	0	0	0	5	0	0	5	15	0	0
C4N7	0.2-1.2	2	6.00	0	0	0	5	0	0	5	5	5	0	0	0	0	0	0	15	5	10
C4N8	1.2-2.2	2	9.00	5	0	5	5	0	0	0	0	0	0	0	5	0	0	0	5	0	0
C4E1	0.2-1.2	97	16.88	0	0	0	5	0	0	5	10	10	0	0	0	0	0	0	25	5	5
C4E2	1.2-2.2	97	16.88	5	0	0	5	0	0	5	0	0	0	0	0	0	0	10	5	0	5
C4E3	0.2-1.2	97	13.50	5	0	0	5	0	0	5	5	5	0	0	0	0	0	5	20	0	10
C4E4	1.2-2.2	97	13.50	5	0	0	5	0	0	5	0	0	0	0	0	0	0	5	0	0	0
C4S1	0.2-1.2	179	67.50	10	0	0	5	0	0	0	5	5	0	5	0	0	0	0	30	5	5
C4S2	0.2-1.2	179	67.50	5	0	0	5	0	0	0	5	0	0	0	0	0	0	0	30	5	0
C4S3	1.2-2.2	179	67.50	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0
C4S4	0.2-1.2	179	20.25	5	0	0	10	0	0	5	5	0	0	0	5	0	0	0	20	5	0
C4S5	0.2-1.2	179	20.25	5	0	0	5	0	0	5	5	0	0	5	15	0	0	0	0	0	0
C4S6	0.2-1.2	179	13.50	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	20	5	0
C4S7	1.2-2.2	179	67.50	10	0	0	0	0	0	0	0	0	0	0	0	0	0	5	20	0	0
C4S8	0.2-1.2	179	13.50	10	0	0	10	0	0	5	10	5	0	0	15	5	0	0	0	0	0
C4W1	0.2-1.2	276	8.55	10	0	0	5	0	0	5	15	0	0	0	0	0	0	0	25	5	10
C4W2	1.2-2.2	276	12.83	10	0	0	0	5	0	5	0	0	0	0	5	0	0	0	40	0	20
C4W3	0.2-1.2	276	12.83	10	0	0	5	0	0	0	10	0	0	0	5	0	0	0	15	0	5
C4W4	1.2-2.2	276	17.10	5	0	0	0	0	0	5	0	0	0	0	5	0	0	0	40	0	10
C4W5	0.2-1.2	276	12.83	10	0	0	5	0	0	0	0	0	0	0	15	0	0	0	30	0	5
C4W6	1.2-2.2	276	17.10	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0
C4W7	0.2-1.2	276	12.83	10	0	0	0	0	0	0	5	0	0	0	0	0	0	0	40	0	20
C4W8	1.2-2.2	276	17.10	10	0	5	5	0	0	0	0	0	0	0	0	0	0	0	25	0	0
C4W9	0.2-1.2	276	12.83	10	0	0	5	5	0	5	5	0	0	0	10	0	5	0	20	0	30
C4W10	1.2-2.2	276	12.83	5	0	0	5	0	0	0	0	0	0	0	10	0	0	0	40	0	15
E1 N1 1	0.2-1.2	348	18.36	5	0	0	10	10	0	10	0	0	0	0	0	0	5	5	5	0	20
E1N1 2	0.2-1.2	348	18.36	5	0	0	5	20	0	0	0	15	0	0	0	0	0	0	5	0	20
E1N1 3	1.2-2.2	348	18.36	5	0	0	0	15	0	5	0	0	10	0	0	0	5	0	0	0	40
E1N1 4	0.2-1.2	348	18.36	0	0	0	0	10	0	5	0	10	10	0	0	0	0	0	0	0	40
E1N1 5	1.2-2.2	348	18.36	0	0	0	0	0	0	5	0	0	10	0	0	0	0	0	0	0	60
E1N1 6	0.2-1.2	348	18.36	0	0	0	0	15	0	10	0	0	5	10	0	0	0	5	0	0	25
E1N1 7	1.2-2.2	348	18.36	0	0	0	5	15	0	10	0	5	5	0	0	0	5	0	0	0	50
E1N2 1	0.2-1.2	348	18.36	20	0	0	0	10	0	0	0	10	0	0	0	10	0	0	5	0	10
E1N2 2	0.2-1.2	348	18.36	10	0	0	0	5	0	0	0	0	0	5	0	0	0	0	0	0	20
E1N2 3	1.2-2.2	348	18.36	15	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	30
E1N2 4	0.2-1.2	348	18.36	0	0	0	0	0	0	5	0	0	0	0	0	0	10	10	0	0	0
E1N2 5	1.2-2.2	348	18.36	5	0	15	0	5	0	0	0	0	0	0	0	0	0	5	0	0	40
E1N2 6	0.2-1.2	348	12.24	5	0	0	5	0	0	5	0	30	0	0	5	0	0	0	5	0	15
E1N2 7	1.2-2.2	348	12.24	5	0	0	5	0	0	0	0	0	0	0	0	0	0	5	0	0	10
E1N2 8	0.2-1.2	348	12.24	5	0	0	5	0	0	0	5	15	5	0	0	0	0	5	5	0	10
E1N2 9	1.2-2.2	348	12.24	5	0	0	5	0	0	0	0	0	0	0	0	0	5	5	0	0	20

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
E1E1 1	0.2-1.2	92	20.40	5	0	0	5	0	0	0	15	10	0	0	0	5	0	0	20	0	0
E1E1 2	0.2-1.2	92	13.60	5	0	5	0	5	0	0	5	0	0	0	0	0	5	0	15	0	30
E1 E1 3	1.2-2.2	92	13.60	5	0	0	10	10	0	0	5	10	0	0	0	0	0	0	5	10	25
E1E1 4	0.2-1.2	92	13.60	0	0	0	0	5	0	0	5	10	10	0	0	5	0	0	15	0	20
E1 E1 5	1.2-2.2	92	13.60	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	20
E1 E1 6	0.2-1.2	92	13.60	5	0	0	0	10	0	0	0	0	10	10	0	0	0	0	0	0	5
E1E1 7	1.2-2.2	92	13.60	10	0	0	0	10	0	0	0	0	5	5	0	0	0	0	0	0	15
E1E2 1	0.2-1.2	92	13.60	5	0	0	5	15	0	0	5	0	5	10	0	0	0	0	5	0	10
E1E2 2	1.2-2.2	92	13.60	5	0	0	0	15	0	0	0	0	0	5	0	0	0	5	0	0	15
E1E2 3	0.2-1.2	92	13.60	5	0	0	0	10	0	10	0	0	0	15	0	0	0	5	0	0	5
E1E2 4	0.2-1.2	92	13.60	5	0	0	0	15	0	0	0	0	0	10	0	0	0	0	5	0	10
E1E2 5	1.2-2.2	92	13.60	5	0	0	0	15	0	0	0	0	0	5	0	0	5	5	0	0	15
E1E2 6	0.2-1.2	92	13.60	5	0	0	0	25	0	0	0	0	5	10	0	0	5	0	5	0	15
E1E2 7	1.2-2.2	92	13.60	5	0	0	0	25	0	10	0	0	0	0	0	0	0	0	0	0	15
E1S1 1	0.2-1.2	171	30.60	5	0	0	5	15	0	5	0	0	0	0	0	0	5	10	0	0	20
E1S1 2	0.2-1.2	171	30.60	5	0	0	5	25	0	5	0	0	5	5	0	0	0	0	5	0	5
E1S1 3	1.2-2.2	171	30.60	5	0	0	10	0	0	0	0	0	0	5	0	0	0	0	10	0	0
E1S1 4	0.2-1.2	171	30.60	5	5	0	10	20	0	0	0	0	0	0	0	0	0	5	5	0	10
E1S1 5	1.2-2.2	171	30.60	5	0	0	10	5	0	0	0	0	0	0	0	0	0	5	10	0	5
E1S1 6	0.2-1.2	171	30.60	10	0	0	5	20	0	10	0	10	0	0	0	0	0	0	5	0	10
E1S1 7	0.2-1.2	171	30.60	5	0	0	10	10	0	20	0	0	0	5	0	0	0	10	0	0	15
E1S1 8	1.2-2.2	171	30.60	10	0	0	5	5	0	15	0	0	0	25	0	0	0	0	0	0	5
E1S2 1	0.2-1.2	171	30.60	5	0	0	0	25	0	0	20	10	10	0	0	0	5	0	5	0	10
E1S2 2	1.2-2.2	171	30.60	0	0	0	5	30	0	5	5	5	0	0	0	0	0	0	5	0	10
E1S2 3	0.2-1.2	171	30.60	5	0	0	0	0	0	0	20	40	0	0	0	0	0	0	5	0	5
E1S2 4	0.2-1.2	171	20.40	5	0	0	0	0	0	0	5	5	0	0	0	5	0	0	15	0	5
E1S2 5	1.2-2.2	171	20.40	5	0	0	0	0	0	0	10	0	0	0	0	0	0	0	10	0	0
E1S2 6	0.2-1.2	171	30.60	0	0	0	10	20	0	0	15	15	0	0	0	0	0	0	0	0	0
E1S2 7	1.2-2.2	171	30.60	10	10	0	10	5	0	0	20	10	0	0	5	5	0	0	10	0	5
E1W1	0.2-1.2	257	17.00	5	0	0	5	0	0	10	0	5	0	10	0	0	0	0	10	0	5
E1W2	1.2-2.2	257	17.00	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	15	0	5
E1W3	0.2-1.2	257	17.00	5	0	0	0	5	0	5	0	0	0	15	0	0	0	10	5	0	5
E1W4	1.2-2.2	257	17.00	5	0	0	5	0	0	0	0	0	0	0	0	0	0	5	5	0	0
E1W5	0.2-1.2	257	17.00	5	0	0	0	10	0	5	20	5	0	0	0	0	0	0	0	0	0
E1W6	1.2-2.2	257	17.00	5	0	0	0	35	0	10	0	0	0	0	0	0	10	20	10	0	0
E1W7	0.2-1.2	257	17.00	10	0	0	5	0	0	10	30	5	0	0	5	0	0	5	10	0	5
E1W8	1.2-2.2	257	17.00	10	0	0	5	5	0	20	10	5	0	0	0	0	0	10	5	0	5
E1W9	0.2-1.2	257	8.50	5	0	0	5	5	0	5	20	5	0	0	10	0	0	0	20	0	10
E1W10	1.2-2.2	257	12.75	5	0	0	0	25	0	5	10	0	0	0	0	0	0	5	15	0	20
E1W11	0.2-1.2	257	25.50	5	0	0	0	40	0	0	20	5	0	0	0	0	0	0	5	0	15
E2N1	0.2-1.2	348	12.24	10	0	0	5	5	0	5	25	15	0	0	0	0	0	0	10	0	5
E2N2	1.2-2.2	348	12.24	10	0	0	10	15	0	5	10	10	0	0	0	0	0	10	10	0	10
E2N3	0.2-1.2	348	12.24	5	0	0	5	5	0	10	20	30	0	0	0	0	0	0	10	0	5
E2N4	1.2-2.2	348	12.24	15	0	0	5	5	0	5	5	0	0	0	0	0	0	5	15	0	5
E2N5	0.2-1.2	348	12.24	5	0	0	5	0	0	5	20	20	10	0	0	0	5	0	10	0	15
E2N6	1.2-2.2	348	12.24	5	0	0	0	5	0	5	0	0	5	0	0	0	5	0	0	0	20
E2N7	0.2-1.2	348	12.24	5	0	0	10	5	0	10	25	25	0	0	5	0	0	0	5	0	10
E2N8	0.2-1.2	348	12.24	5	0	0	5	10	0	10	10	10	0	0	5	0	0	0	10	0	15
E2N9	1.2-2.2	348	12.24	5	0	0	5	10	0	5	0	0	5	0	0	0	5	0	0	0	30
E2N10	0.2-1.2	348	22.95	0	0	0	5	20	0	15	15	20	5	0	0	0	5	0	5	0	5
E2N11	1.2-2.2	348	22.95	10	0	0	5	40	0	15	5	0	5	0	0	0	10	0	0	0	10
E2N12	0.2-1.2	348	22.95	0	0	0	10	15	0	5	10	10	0	0	0	0	5	0	10	0	10
E2N13	1.2-2.2	348	22.95	5	0	0	0	5	0	5	0	0	0	0	0	0	0	0	0	0	35
E2N14	0.2-1.2	348	22.95	5	0	0	20	5	0	5	10	10	10	0	0	0	0	0	5	0	25
E2N15	0.2-1.2	348	27.54	5	0	0	10	5	0	10	5	5	10	0	0	5	5	0	5	0	20
E2N16	1.2-2.2	348	27.54	5	0	0	0	5	0	10	0	0	5	0	0	0	10	0	0	0	45
E2N17	0.2-1.2	348	27.54	10	0	0	10	0	0	10	15	5	5	5	0	0	0	0	25	0	15
E2N18	0.2-1.2	348	18.36	15	0	0	5	5	0	10	5	0	5	5	0	0	10	0	0	0	30
E2N19	1.2-2.2	348	18.36	10	0	0	5	0	15	10	0	0	5	0	0	0	5	5	5	0	30
E2N20	0.2-1.2	348	12.24	5	0	0	5	5	0	10	5	10	5	0	5	0	5	5	10	0	35
E2N21	1.2-2.2	348	12.24	10	0	0	0	50	0	0	0	0	10	0	0	0	0	0	0	0	30
E2E1	0.2-1.2	82	30.60	5	0	0	0	0	0	0	10	5	0	5	0	0	0	0	10	0	10
E2E2	1.2-2.2	82	30.60	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
E2E3	0.2-1.2	82	17.00	20	0	0	0	0	0	15	5	10	5	5	0	0	5	0	10	0	20
E2E4	1.2-2.2	82	17.00	10	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	30
E2E5	0.2-1.2	82	13.60	10	0	0	5	0	0	10	10	25	0	5	0	0	0	5	5	0	10
E2E6	1.2-2.2	82	13.60	5	5	0	0	10	0	20	0	0	0	10	0	0	0	0	0	0	10
E2E7	0.2-1.2	82	13.60	5	0	0	5	5	0	5	5	0	0	5	0	0	0	5	15	0	5
E2E8	1.2-2.2	82	13.60	15	0	0	5	5	0	5	0	0	0	0	0	0	5	5	5	0	15
E2E9	0.2-1.2	82	17.00	5	0	0	0	5	0	10	10	0	5	0	0	0	0	0	15	0	5
E2E10	1.2-2.2	82	17.00	10	0	0	0	0	0	5	0	0	0	5	0	0	0	0	15	0	5
E2E11	0.2-1.2	82	17.00	5	0	0	5	0	0	20	10	0	0	5	0	0	0	5	10	0	5
E2E12	1.2-2.2	82	17.00	5	0	0	5	0	0	0	5	0	0	0	0	0	0	0	15	0	10
E2E13	0.2-1.2	82	13.60	10	0	0	5	0	0	10	10	5	0	0	5	0	5	5	0	0	0

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
E2E14	1.2-2.2	82	13.60	5	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	30
E2E15	0.2-1.2	82	17.00	5	0	0	5	0	0	5	15	15	0	0	5	0	5	0	5	0	10
E2E16	1.2-2.2	82	17.00	5	0	0	5	0	0	0	0	0	0	0	0	0	5	0	0	0	80
E2E17	0.2-1.2	82	30.60	5	0	0	5	0	0	5	5	0	5	0	0	0	0	5	5	0	25
E2E18	1.2-2.2	82	30.60	5	0	0	0	0	0	5	0	0	0	0	0	0	10	5	0	0	20
E2S1	0.2-1.2	172	40.80	5	0	0	15	0	0	20	0	0	0	0	0	0	0	15	10	0	5
E2S2	1.2-2.2	172	40.80	10	0	0	5	0	0	5	0	0	0	0	0	0	5	5	0	0	15
E2S3	0.2-1.2	172	68.00	5	0	0	5	10	0	10	10	0	0	10	0	0	0	0	5	0	5
E2S4	1.2-2.2	172	68.00	30	0	0	0	0	0	0	0	0	0	0	0	0	10	10	0	0	15
E2S5	0.2-1.2	172	71.40	0	0	0	5	0	0	0	5	0	0	0	10	0	0	10	25	0	10
E2S6	0.2-1.2	172	71.40	5	0	0	10	0	0	0	5	5	0	0	0	0	0	0	10	0	10
E2S7	0.2-1.2	172	71.40	5	0	0	5	0	0	10	10	0	0	10	0	0	0	0	5	0	10
E2S8	1.2-2.2	172	71.40	5	0	0	5	0	0	5	0	0	0	0	0	0	0	0	5	0	5
E2S9	0.2-1.2	172	71.40	10	0	0	5	0	0	5	0	0	0	5	0	0	0	10	10	0	5
E2S10	1.2-2.2	172	71.40	5	0	0	0	0	10	0	0	0	0	0	0	0	5	5	10	0	10
E2S11	0.2-1.2	172	71.40	5	0	0	0	0	0	0	0	5	0	0	0	0	0	5	5	0	10
E2S12	0.2-1.2	172	71.40	10	0	0	0	0	0	0	5	5	0	0	0	5	0	0	5	0	5
E2S13	1.2-2.2	172	71.40	5	0	0	5	0	0	5	0	0	0	0	0	0	0	5	5	0	20
E2S14	0.2-1.2	172	91.80	15	0	0	5	0	0	0	5	5	0	0	0	0	0	0	10	0	20
E2S15	1.2-2.2	172	91.80	5	0	0	5	0	0	5	0	0	0	0	0	0	5	0	5	0	40
E2S16	0.2-1.2	172	61.20	10	0	0	5	0	0	10	20	5	0	0	0	0	0	0	10	0	10
E2S17	1.2-2.2	172	61.20	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
E2S18	0.2-1.2	172	61.20	5	0	0	5	5	0	10	15	0	0	15	0	0	0	0	10	0	5
E2S19	1.2-2.2	172	61.20	5	0	0	5	5	0	0	0	0	0	0	0	0	0	0	10	0	0
E2S20	0.2-1.2	172	61.20	10	0	0	5	5	0	5	5	5	0	5	0	0	0	0	10	0	10
E2S21	1.2-2.2	172	61.20	5	0	0	5	5	0	5	0	5	0	0	0	0	0	5	10	0	5
E2W1	0.2-1.2	260	25.50	5	0	0	0	10	0	15	0	0	0	0	0	0	0	5	5	0	5
E2W2	1.2-2.2	260	25.50	5	0	0	5	0	0	0	5	0	0	0	0	0	5	5	15	0	5
E2W3	0.2-1.2	260	17.00	10	0	0	10	10	0	5	0	0	0	0	5	0	5	5	5	0	15
E2W4	1.2-2.2	260	17.00	10	0	0	5	0	0	0	0	0	0	0	10	0	0	10	15	0	5
E2W5	0.2-1.2	260	17.00	5	0	0	5	0	0	5	0	0	0	0	20	0	0	15	30	0	5
E2W6	0.2-1.2	260	17.00	5	0	0	10	5	0	5	0	0	5	10	0	0	0	0	5	0	40
E2W7	1.2-2.2	260	17.00	10	0	0	0	15	0	5	10	0	0	20	0	0	0	20	0	0	0
E2W8	0.2-1.2	260	17.00	5	0	0	5	0	0	5	5	0	0	5	0	0	10	0	0	0	40
E2W9	1.2-2.2	260	17.00	5	0	0	0	5	0	10	15	0	0	0	0	0	5	5	5	0	15
E2W10	0.2-1.2	260	17.00	5	0	0	15	0	0	5	0	0	0	0	10	0	0	15	30	0	10
E2W11	0.2-1.2	260	17.00	5	0	0	15	0	0	0	0	0	0	0	5	0	5	10	15	0	15
E2W12	1.2-2.2	260	17.00	5	0	0	5	0	0	0	0	0	0	0	5	0	10	0	25	0	10
E2W13	0.2-1.2	260	31.88	0	0	0	5	0	0	0	0	0	0	0	0	0	0	5	20	0	5
E2W14	1.2-2.2	260	31.88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	15	0	0
E3N1	0.2-1.2	0	22.50	5	0	0	0	0	0	0	5	0	0	0	0	0	5	5	15	0	30
E3N2	1.2-2.2	0	22.50	5	0	0	5	0	0	5	10	0	0	5	0	0	0	10	15	0	20
E3N3	0.2-1.2	0	22.50	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	10	0	40
E3N4	1.2-2.2	0	22.50	5	0	0	5	0	0	10	15	5	0	0	0	0	0	5	10	0	15
E3N5	0.2-1.2	0	22.50	0	0	5	5	0	0	0	10	0	5	0	0	0	0	0	10	0	25
E3N6	1.2-2.2	0	22.50	5	0	0	5	0	0	10	15	0	0	0	0	0	0	0	0	0	0
E3N7	0.2-1.2	0	15.00	5	0	0	5	5	0	5	5	0	0	5	0	0	5	0	5	0	30
E3N8	1.2-2.2	0	15.00	5	0	0	5	0	0	5	5	5	0	0	0	0	0	5	5	0	20
E3N9	0.2-1.2	0	15.00	5	0	0	5	0	0	5	5	0	0	5	5	0	5	5	10	0	25
E3N10	1.2-2.2	0	15.00	5	0	0	5	5	0	5	5	0	0	0	5	0	0	0	10	0	15
E3N11	0.2-1.2	0	22.50	0	0	0	10	20	0	10	5	0	0	5	0	0	0	20	5	0	5
E3N12	1.2-2.2	0	22.50	10	0	0	10	5	5	5	5	0	0	5	0	0	10	10	5	0	5
E3N13	0.2-1.2	0	22.50	5	0	0	10	0	5	5	20	0	0	0	0	0	0	5	10	0	10
E3N14	0.2-1.2	0	22.50	0	0	0	5	0	0	5	5	0	5	5	0	0	5	5	5	0	15
E3N15	1.2-2.2	0	22.50	5	0	0	5	5	0	0	5	0	0	10	0	0	0	10	5	0	10
E3E1	0.2-1.2	90	30.38	5	0	0	5	0	0	5	10	0	0	0	0	0	0	5	10	0	0
E3E2	1.2-2.2	90	30.38	10	0	5	0	0	0	10	5	0	0	5	0	0	5	5	5	0	5
E3E3	0.2-1.2	90	30.38	5	0	5	15	0	0	5	15	0	0	0	0	0	0	0	10	0	5
E3E4	0.2-1.2	90	16.88	5	0	5	5	0	0	0	10	10	0	0	0	0	0	5	10	0	5
E3E5	1.2-2.2	90	16.88	0	0	5	5	0	0	5	5	0	0	5	0	0	0	0	5	0	5
E3E6	0.2-1.2	90	16.88	5	0	10	5	0	0	5	10	0	0	0	5	0	0	0	20	0	5
E3E7	0.2-1.2	90	13.50	0	0	0	0	0	0	5	10	5	0	0	0	0	0	5	20	0	5
E3E8	1.2-2.2	90	13.50	5	0	5	0	0	0	10	5	0	0	5	0	0	0	0	20	0	0
E3E9	0.2-1.2	90	13.50	0	0	0	10	0	0	10	10	0	0	0	5	0	0	5	10	0	0
E3E10	0.2-1.2	90	13.50	0	0	0	5	0	0	10	5	0	0	0	5	0	0	5	10	0	0
E3E11	0.2-1.2	90	25.31	5	0	0	5	0	0	10	5	0	0	0	5	0	0	5	15	0	0
E3E12	0.2-1.2	90	30.38	0	0	0	15	0	0	0	10	0	0	5	0	0	0	0	20	0	5
E3S1	0.2-1.2	180	40.50	5	0	0	5	0	0	25	5	0	0	5	0	0	5	15	5	0	15
E3S2	1.2-2.2	180	40.50	30	0	0	10	0	0	20	5	5	0	0	5	0	5	5	5	0	5
E3S3	0.2-1.2	180	40.50	10	0	0	10	5	0	20	5	0	0	0	0	0	5	10	5	0	10
E3S4	0.2-1.2	180	27.00	20	0	10	0	0	0	5	0	0	0	0	0	0	0	10	10	0	0
E3S5	1.2-2.2	180	33.75	5	0	5	0	5	0	10	0	0	0	0	0	0	5	5	15	0	5
E3S6	0.2-1.2	180	33.75	10	0	5	5	0	5	5	5	0	0	0	0	0	5	10	5	0	5
E3S7	1.2-2.2	180	33.75	10	0	5	5	5	0	10	5	0	0	0	0	0	5	15	10	0	10

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
E3S8	0.2-1.2	180	27.00	5	0	0	5	0	0	15	10	20	0	0	0	0	0	5	15	0	0
E3S9	1.2-2.2	180	27.00	5	0	20	0	0	0	15	10	0	0	0	5	0	0	5	5	0	0
E3S10	0.2-1.2	180	13.50	5	0	5	10	0	0	10	5	0	0	0	0	0	0	10	5	0	10
E3S11	1.2-2.2	180	13.50	0	0	30	10	0	0	15	5	0	0	0	0	0	0	10	5	0	0
E3S12	0.2-1.2	180	50.63	5	0	5	5	0	0	15	5	0	0	5	5	0	0	5	5	0	0
E3S13	1.2-2.2	180	50.63	5	0	10	5	0	0	5	0	0	0	0	0	0	0	5	10	0	0
E3S14	0.2-1.2	180	60.75	5	0	5	10	0	0	10	10	0	0	5	5	0	0	10	5	0	0
E3S15	1.2-2.2	180	60.75	0	0	0	5	5	0	10	5	0	0	0	5	0	0	10	10	0	0
E3S16	0.2-1.2	180	60.75	5	0	5	0	0	15	15	10	0	0	0	5	0	0	10	5	0	0
E3S17	1.2-2.2	180	60.75	5	0	0	5	0	0	15	5	0	0	5	0	0	0	10	5	0	0
E3W1	0.2-1.2	270	32.06	5	0	0	5	0	0	5	0	0	0	0	0	0	0	10	10	0	5
E3W2	1.2-2.2	270	32.06	5	0	0	0	0	0	10	5	0	0	0	10	0	0	10	5	0	5
E3W3	0.2-1.2	270	19.24	5	0	0	5	5	0	20	15	0	0	0	0	5	5	10	5	0	0
E3W4	0.2-1.2	270	32.06	5	0	0	5	0	0	15	5	0	0	10	5	0	0	15	0	0	5
E3W5	1.2-2.2	270	32.06	5	0	0	5	0	0	5	5	0	0	5	0	0	0	10	5	0	0
E3W6	0.2-1.2	270	17.10	5	0	0	5	0	0	20	5	0	0	0	5	0	0	20	0	0	0
E3W7	1.2-2.2	270	17.10	5	0	5	0	5	0	10	0	0	0	0	10	0	0	10	5	0	5
E3W8	0.2-1.2	270	12.83	0	0	5	0	0	0	10	10	0	0	0	5	0	0	0	5	0	0
E3W9	1.2-2.2	270	12.83	5	0	10	0	0	0	15	5	0	0	0	5	0	0	10	0	0	0
E3W10	0.2-1.2	270	12.83	5	5	0	5	0	15	10	5	5	0	0	5	0	0	5	15	0	0
E3W11	1.2-2.2	270	12.83	5	0	5	5	0	0	0	10	0	0	0	5	0	0	0	15	0	0
E3W12	0.2-1.2	270	21.38	10	0	0	0	0	0	5	5	0	0	0	5	0	5	10	5	0	10
E3W13	1.2-2.2	270	21.38	10	0	0	5	0	0	10	0	0	0	0	10	0	0	10	10	0	5
E4N1	0.2-1.2	48	24.30	5	0	0	5	0	0	5	15	10	0	0	5	0	0	0	10	0	0
E4N2	1.2-2.2	48	24.30	5	0	10	0	0	0	5	0	0	0	0	0	0	0	5	10	0	0
E4N3	0.2-1.2	48	18.90	15	0	0	0	5	0	10	0	0	0	0	10	0	0	0	10	0	5
E4N4	1.2-2.2	48	18.90	5	0	5	0	0	0	5	0	0	0	0	0	0	0	0	5	0	5
E4N5	0.2-1.2	48	13.50	5	0	25	10	0	0	0	5	5	0	5	0	0	0	0	5	0	0
E4N6	1.2-2.2	48	13.50	5	0	5	5	0	0	0	0	0	0	0	0	0	0	0	5	0	0
E4N7	0.2-1.2	48	13.50	5	0	25	5	0	0	5	5	5	0	0	0	0	0	0	5	5	5
E4N8	1.2-2.2	48	13.50	5	0	10	0	0	0	5	0	0	0	0	0	0	5	0	5	0	5
E4N9	0.2-1.2	48	24.30	0	0	70	0	0	0	0	0	5	10	0	0	0	0	0	0	0	10
E4N10	0.2-1.2	48	24.30	0	0	70	0	0	0	15	0	0	0	0	5	0	5	0	0	0	5
E4N11	0.2-1.2	48	24.30	5	0	10	5	0	0	5	0	5	0	0	10	0	5	0	0	0	0
E4N12	0.2-1.2	48	20.25	5	0	5	5	0	0	15	0	5	0	0	15	0	0	0	0	0	0
E4N13	0.2-1.2	48	10.80	5	0	10	0	0	0	10	10	5	0	0	0	0	0	0	5	0	0
E4N14	1.2-2.2	48	10.80	5	0	5	5	0	0	5	5	5	5	5	0	0	0	5	5	0	5
E4E1	0.2-1.2	140	10.65	10	0	0	0	0	0	10	10	10	0	0	5	0	0	0	5	0	0
E4E2	1.2-2.2	140	15.98	10	0	0	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0
E4E3	0.2-1.2	140	15.98	10	0	0	0	0	0	5	15	5	0	0	0	0	0	0	10	0	0
E4E4	1.2-2.2	140	15.98	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
E4E5	0.2-1.2	140	10.65	10	0	20	5	0	0	10	10	5	0	0	0	0	0	0	10	0	5
E4E6	1.2-2.2	140	15.98	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
E4E7	0.2-1.2	140	26.63	10	0	5	0	0	0	5	10	5	0	0	0	0	0	0	0	0	0
E4E8	0.2-1.2	140	39.94	5	0	5	0	0	0	5	5	0	0	0	0	0	0	5	5	0	0
E4E9	0.2-1.2	140	39.94	10	0	5	5	0	0	5	5	0	0	0	0	0	5	5	5	5	25
E4E10	1.2-2.2	140	39.94	5	0	0	0	0	0	5	0	0	0	0	0	0	10	5	5	0	15
E4E11	0.2-1.2	140	7.99	5	0	30	5	0	0	0	5	5	0	0	0	0	0	0	0	15	0
E4E12	1.2-2.2	140	7.99	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5
E4S1	0.2-1.2	228	15.98	15	0	0	0	0	0	5	0	0	0	0	10	0	0	5	5	0	0
E4S2	1.2-2.2	228	15.98	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
E4S3	0.2-1.2	228	23.96	10	0	0	0	0	0	10	15	0	0	0	5	0	0	0	5	0	0
E4S4	1.2-2.2	228	23.96	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
E4S5	0.2-1.2	228	5.33	5	0	40	0	0	0	5	10	5	0	0	0	0	5	5	5	0	5
E4S6	1.2-2.2	228	5.33	5	0	20	0	0	0	0	0	0	0	0	0	0	5	0	5	0	40
E4S7	0.2-1.2	228	21.30	10	0	5	5	0	0	10	10	5	0	5	0	0	0	0	5	0	0
E4S8	1.2-2.2	228	21.30	5	0	10	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
E4W1	0.2-1.2	323	16.20	5	0	10	0	0	0	5	10	0	0	5	0	0	0	0	0	0	5
E4W2	1.2-2.2	323	16.20	5	0	5	0	0	0	5	5	0	5	5	0	0	0	5	5	0	5
E4W3	0.2-1.2	323	2.70	0	0	10	0	0	0	25	10	10	0	0	0	0	0	0	10	0	0
E4W4	1.2-2.2	323	16.20	10	0	0	0	5	0	10	15	0	0	0	0	0	0	0	10	0	0
E4W5	0.2-1.2	323	13.50	5	0	30	0	0	0	5	5	0	0	5	0	0	0	0	5	0	5
E4W6	1.2-2.2	323	13.50	5	0	20	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
E4W7	0.2-1.2	323	8.10	5	0	30	5	0	0	5	0	5	5	10	0	0	0	0	5	0	5
E4W8	0.2-1.2	323	8.10	5	0	10	0	0	0	5	10	10	5	0	0	0	0	0	0	0	0
E4W9	1.2-2.2	323	8.10	5	0	0	0	0	0	10	10	0	5	5	0	0	0	0	5	0	5
E4W10	0.2-1.2	323	8.10	5	0	40	0	0	0	5	5	5	0	0	0	0	5	0	5	0	20
E4W11	1.2-2.2	323	18.90	5	0	45	0	0	0	0	10	5	5	0	0	0	0	0	10	0	10
E5N1	0.2-1.2	3	13.77	5	0	5	5	0	5	15	5	5	0	5	0	0	0	10	5	0	10
E5N2	1.2-2.2	3	13.77	5	0	5	0	0	0	10	0	0	0	5	0	0	5	10	0	0	15
E5N3	0.2-1.2	3	13.77	5	0	5	5	5	5	20	5	5	10	5	0	0	5	5	0	0	15
E5N4	1.2-2.2	3	13.77	5	0	5	10	0	0	20	0	0	0	5	0	0	5	10	5	0	10
E5N5	0.2-1.2	3	13.77	0	0	5	5	5	5	15	5	5	10	0	0	0	5	5	5	0	15
E5N6	0.2-1.2	3	13.77	5	0	5	10	5	0	5	5	5	5	0	5	0	5	5	0	0	5

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
E5N7	1.2-2.2	3	13.77	5	0	5	5	0	0	5	5	0	0	0	0	0	5	5	0	0	15
E5N8	0.2-1.2	3	9.18	5	0	5	5	10	0	10	0	0	5	0	5	0	5	5	0	0	5
E5N9	1.2-2.2	3	9.18	5	0	5	5	0	0	5	0	0	0	0	0	0	5	0	5	0	10
E5N10	0.2-1.2	3	13.77	5	0	5	5	0	0	5	5	5	10	0	0	0	0	0	5	0	10
E5N11	1.2-2.2	3	13.77	5	0	5	5	0	0	5	0	0	0	0	0	0	5	5	5	0	15
E5N12	0.2-1.2	3	13.77	10	0	5	5	0	0	10	5	5	5	0	0	0	5	5	5	0	10
E5N13	1.2-2.2	3	13.77	5	0	5	10	0	20	5	0	0	0	0	0	0	15	5	5	0	5
E5N14	0.2-1.2	3	9.18	5	0	0	0	0	0	5	5	0	0	0	0	0	5	0	10	0	10
E5N15	1.2-2.2	3	9.18	5	0	0	5	0	0	0	5	0	0	0	0	0	5	0	0	0	40
E5E1	0.2-1.2	95	10.20	5	0	10	0	0	0	5	5	5	0	0	0	0	0	5	5	0	0
E5E2	1.2-2.2	95	10.20	10	0	5	0	0	0	5	5	0	0	0	0	0	5	5	0	0	5
E5E3	0.2-1.2	95	3.40	5	0	5	5	0	0	5	0	0	0	5	0	0	0	0	10	0	0
E5E4	0.2-1.2	95	15.30	5	0	5	0	0	0	10	0	5	0	0	0	5	0	0	5	0	10
E5E5	1.2-2.2	95	15.30	5	0	5	0	0	0	0	0	0	0	0	0	0	0	5	0	0	15
E5E6	0.2-1.2	95	10.20	5	0	5	5	10	5	10	5	10	0	5	0	0	0	5	5	0	15
E5E7	1.2-2.2	95	10.20	10	0	10	5	0	0	5	0	5	0	0	0	0	0	5	5	0	0
E5E8	0.2-1.2	95	10.20	10	0	15	5	0	0	15	5	5	0	5	0	0	0	15	5	0	5
E5E9	0.2-1.2	95	6.80	5	0	10	0	0	5	10	5	10	0	0	0	0	0	5	5	0	0
E5E10	1.2-2.2	95	6.80	10	0	15	5	5	0	10	0	0	0	0	0	0	0	5	5	5	5
E5E11	0.2-1.2	95	6.80	5	0	5	5	5	0	10	5	5	0	5	0	0	0	5	0	0	0
E5E12	1.2-2.2	95	10.20	5	0	5	0	0	0	5	0	0	0	5	0	0	0	5	5	0	20
E5S1	0.2-1.2	183	6.80	5	0	5	0	0	0	5	5	0	0	0	5	0	0	5	5	0	5
E5S2	1.2-2.2	183	6.80	5	0	0	5	0	0	0	0	0	0	0	5	0	0	0	15	0	20
E5S3	0.2-1.2	183	13.60	5	0	5	5	0	0	10	5	0	5	0	0	0	0	10	5	0	5
E5S4	1.2-2.2	183	20.40	10	0	5	5	0	0	5	5	0	5	0	0	0	0	5	5	0	5
E5S5	0.2-1.2	183	20.40	20	0	5	5	0	0	10	5	0	0	0	0	0	0	5	20	0	0
E5S6	1.2-2.2	183	30.60	10	0	5	0	5	0	20	5	0	0	0	5	0	0	5	5	0	5
E5S7	0.2-1.2	183	20.40	5	0	5	5	0	5	0	5	0	0	0	5	0	0	0	20	0	5
E5S8	1.2-2.2	183	30.60	10	0	5	0	5	0	5	5	0	0	0	0	0	0	5	5	0	5
E5S9	0.2-1.2	183	30.60	5	0	5	0	0	0	5	10	0	0	5	0	0	0	5	10	0	5
E5S10	1.2-2.2	183	40.80	10	0	5	5	0	5	0	0	0	0	0	5	0	5	10	0	0	0
E5S11	0.2-1.2	183	20.40	5	0	10	5	0	0	10	5	0	0	0	5	0	0	5	10	0	5
E5S12	1.2-2.2	183	40.80	10	0	10	5	0	0	0	5	0	0	0	5	0	0	5	0	0	5
E5S13	0.2-1.2	183	20.40	5	0	5	0	0	0	5	10	0	0	0	0	0	0	5	10	0	5
E5S14	1.2-2.2	183	40.80	5	5	10	5	0	5	0	5	0	0	0	0	0	0	5	5	0	5
E5S15	0.2-1.2	183	27.20	5	0	0	5	0	0	0	5	0	0	0	0	0	0	0	35	0	5
E5W1	0.2-1.2	274	12.75	10	0	5	0	5	0	10	5	0	0	0	0	0	0	10	10	0	5
E5W2	1.2-2.2	274	12.75	5	0	5	0	0	10	10	5	0	0	0	5	0	0	5	20	0	5
E5W3	0.2-1.2	274	12.75	5	0	5	5	0	0	10	5	0	0	0	0	0	0	5	5	10	0
E5W4	1.2-2.2	274	12.75	5	0	5	5	0	0	5	5	0	0	0	5	0	5	10	0	0	15
E5W5	0.2-1.2	274	12.75	5	0	5	0	0	0	5	5	5	0	0	0	0	0	5	5	0	5
E5W6	1.2-2.2	274	12.75	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	20	0	5
E5W7	0.2-1.2	274	12.75	5	0	0	0	0	0	5	5	0	0	0	0	0	0	5	5	0	0
E5W8	1.2-2.2	274	12.75	5	0	5	5	5	0	0	0	0	0	0	0	0	0	5	10	0	5
E5W9	0.2-1.2	274	4.25	5	0	0	0	0	0	5	5	5	0	5	0	0	5	0	5	0	15
E5W10	1.2-2.2	274	8.50	0	0	5	0	0	0	5	10	5	0	0	0	0	5	5	10	0	5
E5W11	0.2-1.2	274	4.25	25	0	5	5	0	0	25	10	0	0	0	5	0	0	10	5	0	0
E5W12	1.2-2.2	274	12.75	10	0	10	0	0	0	20	0	0	0	0	5	0	0	10	5	0	0
E5W13	0.2-1.2	274	6.38	0	0	0	5	0	0	20	0	0	0	0	10	0	0	5	15	0	0
E6N1	0.2-1.2	3	9.00	0	0	0	10	5	0	5	20	0	0	0	0	0	5	5	20	0	15
E6N2	1.2-2.2	3	9.00	5	0	0	5	5	0	5	15	0	0	0	5	0	10	5	10	0	5
E6N3	0.2-1.2	3	9.00	0	0	0	20	0	0	10	10	0	0	0	0	0	10	0	5	0	10
E6N4	1.2-2.2	3	9.00	0	0	0	20	0	0	5	10	0	5	0	0	0	0	0	5	0	10
E6N5	0.2-1.2	3	6.00	0	0	0	10	0	0	10	20	0	0	0	5	0	5	5	20	0	10
E6N6	1.2-2.2	3	6.00	5	0	0	20	0	0	5	20	0	0	0	0	0	5	5	20	0	10
E6N7	0.2-1.2	3	9.00	5	0	0	10	5	0	10	15	0	0	5	5	0	5	0	20	0	15
E6N8	1.2-2.2	3	9.00	5	0	0	15	0	0	0	15	0	0	0	0	0	0	0	15	0	15
E6N9	0.2-1.2	3	9.00	5	0	0	10	0	0	5	5	0	5	0	0	0	5	5	5	0	15
E6N10	0.2-1.2	3	9.00	0	0	0	15	0	0	5	10	0	0	0	0	0	5	0	10	0	20
E6E1	0.2-1.2	96	13.50	0	0	0	10	0	0	5	10	0	5	0	0	0	5	0	10	0	20
E6E2	1.2-2.2	96	13.50	5	0	0	5	5	0	5	15	0	5	0	0	0	0	0	10	0	20
E6E3	0.2-1.2	96	10.13	0	0	0	5	0	20	10	10	0	5	5	0	0	5	5	5	0	25
E6E4	0.2-1.2	96	10.13	0	0	0	5	0	0	5	20	0	0	0	0	0	0	5	15	0	20
E6E5	1.2-2.2	96	10.13	5	0	0	5	0	0	5	20	0	0	0	0	0	0	5	20	0	10
E6E6	0.2-1.2	96	3.38	0	0	0	5	0	0	10	20	0	5	0	0	0	10	0	20	0	20
E6E7	1.2-2.2	96	6.75	0	0	0	5	0	0	10	20	0	0	0	0	0	5	0	20	0	20
E6E8	0.2-1.2	96	10.13	0	0	0	5	0	0	5	20	0	0	0	0	0	0	0	20	0	10
E6E9	1.2-2.2	96	10.13	0	0	0	5	5	0	5	20	0	0	0	0	0	0	5	25	0	5
E6S1	0.2-1.2	178	13.50	0	0	0	10	0	0	20	15	0	5	0	5	0	5	5	10	0	10
E6S2	0.2-1.2	178	20.25	0	0	5	5	5	0	10	15	0	5	0	0	0	5	5	15	0	5
E6S3	1.2-2.2	178	50.63	5	0	0	5	0	0	10	10	0	0	0	0	0	5	10	15	0	15
E6S4	0.2-1.2	178	13.50	5	0	0	10	0	0	5	15	0	0	0	0	0	5	0	15	0	10
E6S5	1.2-2.2	178	33.75	10	0	0	5	0	5	5	10	0	0	0	0	0	0	0	5	0	10
E6S6	0.2-1.2	178	13.50	5	0	0	10	0	0	5	20	0	0	0	5	0	5	5	15	0	5

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
E6S7	1.2-2.2	178	33.75	5	0	0	5	5	5	5	10	0	0	0	0	0	0	5	15	0	5
E6S8	0.2-1.2	178	20.25	5	0	0	10	0	0	5	10	0	5	0	5	0	5	5	15	0	0
E6S9	0.2-1.2	178	20.25	5	0	0	5	0	0	5	5	0	0	0	0	0	0	5	10	0	10
E6S10	0.2-1.2	178	20.25	5	0	0	10	0	0	5	10	0	0	0	0	0	5	5	5	0	10
E6W1	0.2-1.2	278	21.38	5	0	0	5	0	0	5	25	0	0	5	0	0	0	5	15	0	5
E6W2	1.2-2.2	278	21.38	10	0	0	5	5	0	5	15	0	0	5	0	0	5	0	10	0	5
E6W3	0.2-1.2	278	21.38	5	0	0	5	0	0	5	20	0	0	0	5	0	0	5	15	0	10
E6W4	0.2-1.2	278	21.38	0	0	0	5	0	0	5	15	0	0	5	0	0	5	0	10	0	10
E6W5	1.2-2.2	278	21.38	5	0	0	0	0	0	5	10	0	0	0	0	0	0	0	10	0	10
E6W6	0.2-1.2	278	8.55	5	0	0	5	0	0	5	5	0	0	5	0	0	10	0	5	0	10
E6W7	1.2-2.2	278	8.55	5	0	0	5	0	0	0	0	0	0	5	0	0	5	0	5	0	10
E7N1	0.2-1.2	11	6.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	70
E7N2	1.2-2.2	11	6.00	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	40	0	10
E7N3	0.2-1.2	11	9.00	5	0	5	0	0	0	0	10	0	0	0	0	0	0	0	30	0	45
E7N4	0.2-1.2	11	12.00	0	0	0	5	5	0	5	5	0	5	5	0	0	0	0	20	0	40
E7N5	1.2-2.2	11	12.00	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	25	0	0
E7N6	0.2-1.2	11	12.00	5	0	0	5	5	0	5	10	0	0	0	0	0	0	0	20	0	40
E7N7	1.2-2.2	11	12.00	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	20	0	0
E7N8	0.2-1.2	11	12.00	5	0	0	5	0	0	5	5	0	5	0	5	0	0	0	40	0	30
E7N9	1.2-2.2	11	12.00	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	85	0	0
E7N10	0.2-1.2	11	9.00	0	0	0	5	5	0	5	5	0	0	5	0	0	0	0	30	5	30
E7N11	1.2-2.2	11	9.00	5	0	0	5	0	0	0	0	0	0	0	5	0	0	0	40	0	5
E7N12	0.2-1.2	11	9.00	5	0	0	10	5	0	10	0	0	0	0	0	0	0	0	15	0	25
E7N13	1.2-2.2	11	9.00	5	0	0	5	0	0	0	0	0	0	0	5	0	0	0	50	0	5
E7N14	0.2-1.2	11	9.00	5	0	0	10	0	0	5	5	0	0	5	0	0	0	5	15	0	25
E7N15	1.2-2.2	11	9.00	0	0	0	5	0	0	0	0	0	0	0	0	0	0	5	40	0	0
E7N16	0.2-1.2	11	9.00	5	0	0	5	0	0	20	10	0	5	15	0	0	0	0	10	0	20
E7E1	0.2-1.2	109	4.28	5	0	0	0	5	0	5	5	0	0	5	0	0	0	5	35	0	5
E7E2	0.2-1.2	109	8.55	5	0	0	0	5	0	5	5	0	0	5	0	0	0	0	25	0	0
E7E3	1.2-2.2	109	8.55	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0
E7E4	0.2-1.2	109	8.55	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	45	0	5
E7E5	1.2-2.2	109	12.83	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0
E7E6	0.2-1.2	109	8.55	10	0	0	5	0	0	10	5	0	0	5	5	0	0	0	40	0	5
E7E7	1.2-2.2	109	12.83	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0
E7E8	0.2-1.2	109	8.55	10	0	0	10	0	0	0	10	0	0	0	0	0	0	0	40	5	5
E7E9	1.2-2.2	109	8.55	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	70	0	5
E7E10	0.2-1.2	109	8.55	10	0	0	10	0	0	0	10	0	0	5	0	0	0	0	20	10	5
E7E11	1.2-2.2	109	8.55	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	0	0
E7E12	0.2-1.2	109	4.28	5	0	5	0	0	0	0	5	0	0	0	0	0	0	0	40	5	30
E7E13	1.2-2.2	109	4.28	5	0	5	0	5	0	0	5	0	0	0	0	0	0	0	30	0	25
E7S1	0.2-1.2	190	13.50	5	0	0	5	0	0	0	5	0	0	0	5	0	0	0	65	0	10
E7S2	0.2-1.2	190	13.50	5	0	0	0	0	0	0	5	0	0	0	5	0	0	0	50	0	10
E7S3	1.2-2.2	190	27.00	5	0	0	0	0	0	0	0	0	0	0	5	0	0	0	40	0	0
E7S4	0.2-1.2	190	13.50	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	50	0	10
E7S5	1.2-2.2	190	27.00	5	0	0	0	0	0	0	0	0	0	5	0	0	0	5	50	0	0
E7S6	0.2-1.2	190	6.75	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	50	0	10
E7S7	0.2-1.2	190	13.50	10	0	0	15	5	0	10	15	0	0	5	0	0	0	0	25	0	5
E7S8	1.2-2.2	190	20.25	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0
E5S9	0.2-1.2	190	13.50	5	0	0	10	5	0	10	5	0	0	15	0	0	0	5	10	0	0
E7S10	1.2-2.2	190	20.25	5	0	0	0	0	0	0	0	0	0	0	5	0	0	0	25	0	0
E7S11	0.2-1.2	190	27.00	10	0	0	10	0	0	10	15	0	0	10	0	0	0	0	40	0	0
E7S12	0.2-1.2	190	27.00	5	0	0	5	0	0	0	5	0	0	0	0	0	0	0	40	0	0
E7S13	1.2-2.2	190	27.00	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	35	0	0
E7S14	0.2-1.2	190	6.75	5	0	0	5	0	0	0	5	0	0	0	5	0	0	0	15	0	0
E7S15	1.2-2.2	190	27.00	5	0	0	0	0	0	0	0	0	0	0	0	0	0	5	30	0	0
E7S16	0.2-1.2	190	27.00	5	0	0	5	0	0	0	5	0	0	0	5	0	0	0	25	0	5
E7S17	1.2-2.2	190	27.00	5	0	0	0	5	0	0	0	0	0	0	0	0	0	5	35	0	0
E7W1	0.2-1.2	285	12.83	10	0	5	5	0	0	5	5	0	5	5	0	0	0	5	20	0	25
E7W2	1.2-2.2	285	12.83	10	0	5	5	0	0	5	0	0	5	5	0	0	5	10	5	0	10
E7W3	0.2-1.2	285	4.28	15	0	5	5	5	0	10	0	0	0	0	5	0	0	10	25	0	10
E7W4	1.2-2.2	285	4.28	10	0	5	5	10	0	5	0	0	0	0	0	0	5	10	10	0	5
E7W5	0.2-1.2	285	21.38	5	0	5	0	10	0	5	5	0	0	0	0	0	0	10	40	0	10
E7W6	1.2-2.2	285	21.38	10	0	0	5	15	0	5	5	0	0	0	5	0	0	10	5	0	0
E7W7	0.2-1.2	285	4.28	5	0	5	5	0	0	5	10	0	0	5	0	0	0	0	15	0	30
E7W8	1.2-2.2	285	4.28	5	0	0	5	0	0	0	0	0	0	0	5	0	0	0	15	0	5
E7W9	0.2-1.2	285	12.83	0	0	0	5	0	0	5	10	0	0	0	5	0	0	0	60	0	10
E7W10	1.2-2.2	285	12.83	5	0	0	5	0	0	0	5	0	0	0	5	0	0	0	80	0	0
E7W11	0.2-1.2	285	12.83	5	0	0	5	10	0	10	10	0	0	5	0	0	0	0	50	0	5
E7W12	1.2-2.2	285	12.83	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0
E7W13	0.2-1.2	285	8.55	5	0	5	5	0	0	15	0	0	0	0	10	0	0	0	50	0	5
E7W14	0.2-1.2	285	4.28	0	0	0	5	0	0	5	0	0	0	0	5	0	5	5	45	0	5
E7W15	1.2-2.2	285	12.83	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	80	0	5
E7W16	0.2-1.2	285	4.28	5	0	0	5	0	0	5	5	0	0	0	5	0	0	5	30	0	10
E7W17	1.2-2.2	285	12.83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	40	0	0

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
E8NA1	0.2-1.2	358	10.80	5	0	5	5	0	0	5	5	0	5	0	0	0	0	0	5	0	50
E8NA2	0.2-1.2	358	5.40	5	0	0	5	0	0	5	5	0	0	0	0	0	0	0	5	0	50
E8NA3	0.2-1.2	358	2.70	10	0	0	5	0	0	5	5	0	0	0	5	0	0	0	5	10	50.
E8NA4	0.2-1.2	358	2.70	5	0	0	5	0	0	5	5	0	5	5	0	0	0	0	5	0	70
E8NA5	1.2-2.2	358	8.10	5	0	10	10	0	0	10	5	0	0	5	0	0	5	10	20	0	5
E8NB6	0.2-1.2	358	8.10	5	0	0	5	0	10	0	0	0	0	0	0	0	10	0	5	0	55
E8NB7	1.2-2.2	358	8.10	10	0	0	5	0	0	5	0	0	0	0	0	0	0	5	10	0	30
E8E1	0.2-1.2	88	12.00	5	0	10	5	0	0	0	10	0	0	0	0	0	0	0	10	0	30
E8E2	1.2-2.2	88	12.00	15	0	5	10	0	5	5	5	0	0	0	0	0	0	0	45	0	5
E8E3	0.2-1.2	88	12.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E8E4	1.2-2.2	88	12.00	10	0	40	5	0	0	0	5	0	0	0	5	0	0	0	20	5	0
E8E5	0.2-1.2	88	12.00	10	0	5	10	0	0	10	10	0	0	0	5	0	0	0	20	0	30
E8E6	1.2-2.2	88	12.00	5	0	20	10	0	0	0	5	0	0	0	5	0	0	0	40	0	0
E8SA1	0.2-1.2	176	18.00	20	0	10	5	0	0	0	5	0	0	0	0	0	0	0	30	0	0
E8SA2	1.2-2.2	176	24.00	10	0	15	5	0	0	5	5	0	0	0	0	0	0	5	35	0	0
E8SB3	0.2-1.2	176	18.00	20	0	20	5	0	0	5	5	0	0	0	0	0	0	0	15	5	0
E8SB4	1.2-2.2	176	18.00	15	0	30	0	0	0	0	5	0	0	0	0	0	0	0	20	0	0
E8SB5	0.2-1.2	176	18.00	10	0	10	5	0	0	0	10	0	0	10	0	0	0	0	30	0	0
E8SB6	1.2-2.2	176	18.00	5	0	5	5	0	0	0	10	0	0	0	0	0	0	5	20	5	0
E8SB7	0.2-1.2	176	6.00	10	0	10	5	0	0	5	5	0	0	0	0	0	5	0	25	0	20
E8SB8	1.2-2.2	176	24.00	10	0	25	0	0	0	0	5	0	0	0	10	0	0	0	40	0	0
E8SB9	0.2-1.2	176	18.00	15	0	5	0	0	0	5	5	0	0	0	0	0	0	0	10	5	10
E8SB10	1.2-2.2	176	24.00	20	0	10	5	0	0	5	0	0	0	0	5	0	0	5	10	0	5
E8WA1	0.2-1.2	268	11.25	5	0	5	0	0	0	5	0	0	0	5	0	0	0	0	5	0	35
E8WA2	1.2-2.2	268	11.25	5	0	5	5	0	0	0	0	0	0	5	0	0	0	0	5	0	50
E8WB3	0.2-1.2	268	11.25	10	0	10	5	0	0	5	20	0	0	0	0	0	0	0	20	0	20
E8WB4	1.2-2.2	268	11.25	20	0	10	5	0	0	0	5	0	0	5	0	0	0	0	15	0	5
E8WB5	0.2-1.2	268	11.25	10	0	10	5	0	0	5	20	0	0	0	0	0	0	0	40	0	5
E8WB6	1.2-2.2	268	11.25	15	0	10	10	0	0	5	5	0	0	0	5	0	0	0	10	5	0
E8WB7	0.2-1.2	268	7.50	5	0	10	5	5	0	5	20	0	0	0	0	0	0	5	20	5	10
E9N1	0.2-1.2	344	9.00	5	0	15	5	0	15	5	10	0	0	0	0	0	0	0	25	5	20
E9N2	1.2-2.2	344	18.00	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0
E9N3	0.2-1.2	344	3.00	5	0	15	5	0	10	5	5	0	5	0	0	0	0	0	10	5	35
E9N4	1.2-2.2	344	6.00	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	5	0	40
E9N5	0.2-1.2	344	9.00	5	0	5	5	0	5	5	5	0	5	0	0	0	0	0	10	0	30
E9N6	1.2-2.2	344	9.00	10	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	10
E9N7	0.2-1.2	344	9.00	5	0	20	5	0	10	5	5	5	5	0	0	0	0	0	10	5	15
E9N8	1.2-2.2	344	9.00	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	5	0	20
E9N9	0.2-1.2	344	6.00	5	0	25	10	0	0	5	5	5	0	0	0	0	5	0	5	15	25
E9N10	0.2-1.2	344	12.00	5	0	0	5	0	0	5	0	0	5	0	0	0	0	5	10	40	25
E9N11	0.2-1.2	344	9.00	5	0	5	10	0	15	5	5	0	0	0	0	0	5	0	0	50	10
R9N12	0.2-1.2	344	9.00	5	0	5	10	0	10	10	5	5	5	0	0	0	0	5	5	35	5
E9N13	1.2-2.2	344	9.00	5	0	25	5	0	0	0	0	0	0	5	0	0	0	0	5	0	10
E9N14	0.2-1.2	344	3.00	5	0	0	5	0	0	5	5	0	0	0	0	5	0	0	5	5	15
E9N15	1.2-2.2	344	3.00	5	0	5	5	5	0	5	0	0	0	0	0	0	0	5	10	5	5
E9N16	0.2-1.2	344	9.00	5	0	5	5	0	0	10	5	0	10	0	0	0	5	0	5	5	15
E9N17	1.2-2.2	344	9.00	5	0	30	5	0	5	5	0	0	0	0	0	0	5	0	10	0	25
E9E1	0.2-1.2	71	3.00	10	0	25	10	0	0	5	0	0	5	0	5	0	0	0	5	5	15
E9E2	1.2-2.2	71	3.00	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
E9E3	0.2-1.2	71	3.00	5	0	0	10	0	25	10	10	0	0	0	5	0	5	0	5	5	5
E9E4	1.2-2.2	71	3.00	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	15
E9E5	0.2-1.2	71	6.00	5	0	25	5	0	5	5	10	0	0	0	5	0	0	0	30	0	0
E9E6	1.2-2.2	71	9.00	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0
E9E7	0.2-1.2	71	3.00	10	0	15	10	0	15	5	5	0	0	0	5	0	10	5	5	5	20
E9E8	1.2-2.2	71	9.00	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5
E9E9	0.2-1.2	71	4.50	5	0	20	5	0	20	0	0	0	0	0	0	0	0	0	10	5	15
E9E10	1.2-2.2	71	18.00	10	0	0	0	0	0	5	0	0	0	0	5	0	0	0	10	0	10
E9S1	0.2-1.2	167	6.75	10	0	5	10	0	0	5	20	0	0	0	0	0	0	5	15	5	5
E9S2	0.2-1.2	167	20.25	5	0	5	5	5	0	5	15	0	0	0	0	0	0	0	35	0	0
E9S3	1.2-2.2	167	20.25	5	0	20	5	0	5	5	0	0	0	0	0	0	0	5	10	0	0
E9S4	0.2-1.2	167	27.00	10	0	5	5	10	0	5	15	0	0	0	0	0	0	0	20	5	5
E9S5	0.2-1.2	167	20.25	5	0	10	5	10	0	10	5	0	0	0	5	0	0	0	20	0	0
E9S6	1.2-2.2	167	27.00	5	0	0	5	0	0	5	5	0	0	5	0	0	0	5	10	0	0
E9S7	0.2-1.2	167	20.25	5	0	5	10	0	15	10	10	0	0	0	5	0	0	5	10	0	0
E9S8	1.2-2.2	167	20.25	5	0	5	0	5	0	5	5	0	0	0	0	0	0	0	15	0	0
E9S9	0.2-1.2	167	6.75	15	0	5	5	0	0	5	5	0	0	5	0	0	0	0	30	0	5
E9S10	0.2-1.2	167	20.25	10	0	10	5	0	15	0	10	0	0	0	0	0	0	0	20	0	5
E9S11	1.2-2.2	167	20.25	15	0	0	5	0	0	0	0	0	0	0	0	0	0	0	15	0	5
E9S12	0.2-1.2	167	20.25	5	0	25	5	5	0	5	5	0	0	0	5	0	0	0	15	5	0
E9S13	1.2-2.2	167	20.25	10	0	5	5	0	0	5	5	0	0	0	0	0	0	5	40	0	5
E9S14	0.2-1.2	167	20.25	5	0	10	5	0	20	5	10	0	0	0	0	0	0	0	10	5	10
E9S15	1.2-2.2	167	20.25	5	0	5	0	0	0	5	0	0	0	0	0	0	0	0	25	0	0
E9S16	0.2-1.2	167	20.25	20	0	5	0	0	0	5	5	0	0	0	0	0	0	0	35	5	5
E9W1	0.2-1.2	249	18.00	10	0	0	0	10	0	5	15	0	5	0	0	0	0	0	10	5	35

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
E9W2	1.2-2.2	249	45.00	10	0	0	0	0	0	5	5	0	0	0	0	0	0	0	5	0	50
E9W3	0.2-1.2	249	24.00	10	0	0	5	0	0	0	15	0	0	0	0	0	0	5	20	5	0
E9W4	1.2-2.2	249	24.00	5	0	5	0	0	0	0	0	0	0	0	5	0	0	5	20	0	0
E9W5	0.2-1.2	249	30.00	10	0	15	5	0	15	5	10	0	0	0	5	0	0	0	25	0	5
E9W6	1.2-2.2	249	30.00	5	0	5	5	0	0	5	0	0	0	0	5	0	0	5	15	0	0
E9W7	0.2-1.2	249	6.00	5	0	0	5	5	0	5	10	0	0	0	0	0	0	0	15	0	5
E9W8	0.2-1.2	249	6.00	10	0	0	10	0	0	10	10	0	0	5	5	0	0	5	20	10	5
E9W9	0.2-1.2	249	9.00	10	0	10	5	20	0	0	15	0	0	0	0	0	0	0	10	10	15
E9W10	1.2-2.2	249	9.00	15	0	10	0	5	0	0	10	0	0	0	0	0	0	0	15	0	20
N1 N1	0.2	325	27.54	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	40	0	5
N1N2	1.2	325	27.54	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0
N1N3	0.2	325	27.54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	10
N1N4	1.2	325	27.54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0
N1N5	0.2	325	27.54	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	10	5	10
N1N6	1.2	325	27.54	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	10
N1N7	0.2	325	27.54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	0	15
N1N8	1.2	325	27.54	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	10
N1N9	0.2	325	4.59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	40
N1N10	1.2	325	4.59	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	5	5
N1N11	0.2	325	22.95	2	0	0	2	0	0	0	5	5	0	0	0	0	0	0	40	0	5
N1N12	1.2	325	22.95	0	2	0	2	0	0	0	2	0	0	0	0	0	0	0	50	0	10
N1N13	0.2	325	22.95	5	0	0	2	0	0	0	0	2	0	0	0	0	0	0	30	0	20
N1N14	1.2	325	22.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0	10
N1N15	0.2	325	22.95	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	20	0	25
N1N16	1.2	325	22.95	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	40
N1N17	0.2	325	27.54	10	0	0	5	0	0	0	5	0	0	0	0	0	0	0	40	0	15
N1N18	1.2	325	27.54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	20
N1N19	0.2	325	27.54	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	25	0	40
N1N20	1.2	325	27.54	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	20
N1N21	0.2	325	22.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	50
N1N22	1.2	325	22.95	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	30	0	15
N1E1	0.2	55	6.12	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	20	0	0
N1E2	1.2	55	6.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0
N1E3	0.2	55	6.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0
N1E4	1.2	55	6.12	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0
N1E5	0.2	55	6.12	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	40	0	5
N1E6	1.2	55	6.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	20
N1E7	0.2	55	6.12	0	0	0	0	0	0	0	10	0	0	0	1	0	0	0	80	0	5
N1E8	1.2	55	6.12	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	0	10
N1E9	0.2	55	6.12	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	40	0	10
N1E10	1.2	55	6.12	10	2	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	5
N1S1	0.2	148	27.16	0	0	0	0	0	0	0	10	10	0	0	0	0	0	0	20	0	0
N1S2	1.2	148	27.16	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	0	0
N1S3	0.2	148	27.16	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	30	0	10
N1S4	1.2	148	27.16	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	0	0
N1S5	0.2	148	27.16	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	20	0	60
N1S6	1.2	148	18.11	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	40	0	5
N1S7	0.2	148	18.11	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	40	5	10
N1S8	1.2	148	18.11	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0
N1S9	0.2	148	27.16	5	0	0	0	0	0	0	5	0	5	0	0	0	0	0	20	0	5
N1S10	1.2	148	27.16	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	40	0	0
N1S11	0.2	148	27.16	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	25	0	2
N1S12	1.2	148	27.16	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	50	0	0
N1S13	0.2	148	27.16	5	5	0	0	0	0	0	20	0	0	0	0	0	0	0	30	0	0
N1S14	1.2	148	27.16	5	0	0	0	0	0	0	10	0	0	0	0	0	0	0	40	0	0
N1S15	0.2	148	18.11	5	5	0	0	0	0	0	15	0	0	0	0	0	0	0	40	0	0
N1S16	1.2	148	18.11	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	50	0	0
N1S17	0.2	148	18.11	2	0	0	0	0	0	0	5	0	0	0	0	0	0	0	40	0	0
N1S18	1.2	148	18.11	0	0	0	0	0	5	0	5	0	0	0	0	0	0	0	50	0	0
N1S19	0.2	148	18.11	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	50	0	5
N1S20	1.2	148	18.11	0	5	0	0	0	0	0	5	0	0	0	0	0	0	0	60	0	0
N1W1	0.2	236	45.26	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	30
N1W2	1.2	236	45.26	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	70	0	20
N1W3	0.2	236	18.11	5	0	0	0	0	0	0	20	0	0	0	0	0	0	0	20	0	5
N1W4	1.2	236	18.11	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	10
N1W5	0.2	236	30.18	5	0	0	0	0	0	0	20	0	0	0	0	0	0	0	25	0	10
N1W6	1.2	236	30.18	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	20
N1W7	0.2	236	30.18	0	0	0	0	0	0	5	5	5	0	0	0	0	0	0	25	0	5
N1W8	1.2	236	30.18	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	60	0	20
N1W9	0.2	236	24.14	5	0	0	0	0	0	0	10	1	0	0	0	0	0	0	60	0	0
N1W10	1.2	236	24.14	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0	20
N1W11	0.2	236	24.14	5	0	0	0	0	0	0	5	5	0	0	0	0	0	0	30	0	5
N1W12	1.2	236	24.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0	10
N1W13	0.2	236	24.14	5	0	0	0	0	0	0	10	10	0	0	0	0	0	0	30	0	5

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
N1W14	1.2	236	24.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	45
N2N1	0.2-1.2	13	16.20	5	0	10	5	5	0	15	20	5	0	0	0	0	0	0	15	0	10
N2N2	1.2-2.2	13	16.20	0	0	20	5	0	0	20	0	0	5	0	0	0	20	5	5	0	40
N2N3	0.2-1.2	13	16.20	5	0	0	5	0	5	20	15	5	0	0	0	0	5	0	10	0	10
N2N4	1.2-2.2	13	16.20	5	0	25	5	5	0	10	0	0	0	0	0	0	5	0	5	0	50
N2N5	0.2-1.2	13	8.10	0	0	0	5	5	0	20	5	5	0	0	5	0	0	5	25	0	0
N2N6	1.2-2.2	13	8.10	5	0	5	10	0	0	15	0	0	0	0	5	0	0	10	20	0	5
N2N7	0.2-1.2	13	10.80	5	0	20	5	0	0	10	10	0	0	0	5	0	5	5	20	0	10
N2N8	0.2-1.2	13	8.10	0	0	10	5	0	0	10	10	5	0	0	5	0	5	0	10	0	10
N2N9	1.2-2.2	13	8.10	5	0	25	5	5	0	10	0	5	0	0	5	5	5	0	10	0	15
N2N10	0.2-1.2	13	4.05	0	0	5	0	5	0	5	10	5	0	0	0	0	0	0	10	0	10
N2N11	1.2-2.2	13	4.05	0	0	30	0	0	5	10	10	0	0	0	5	0	5	0	10	0	25
N2N12	0.2-1.2	13	16.20	5	0	5	5	0	0	15	15	5	0	0	0	5	0	0	10	0	5
N2N13	1.2-2.2	13	16.20	5	0	15	5	5	0	5	0	0	0	0	0	0	10	0	10	0	30
N2N14	0.2-1.2	13	16.20	0	0	0	5	5	0	15	10	0	0	0	0	0	0	0	25	0	5
N2N15	0.2-1.2	13	20.25	5	0	5	5	0	0	10	5	0	0	5	5	0	5	0	10	0	5
N2N16	1.2-2.2	13	20.25	5	0	15	5	0	0	10	0	0	0	0	5	0	5	0	15	0	10
N2N17	0.2-1.2	13	20.25	0	0	15	10	0	0	5	15	0	0	0	5	0	0	0	30	0	5
N2E1	0.2-1.2	107	15.00	5	0	0	5	0	0	15	5	5	0	5	5	0	0	5	10	0	10
N2E2	1.2-2.2	107	15.00	5	0	0	5	0	0	5	0	0	0	0	5	0	5	5	10	0	10
N2E3	0.2-1.2	107	12.00	0	0	0	10	0	0	10	10	5	0	0	0	0	5	5	10	0	10
N2E4	1.2-2.2	107	12.00	5	5	0	5	0	0	10	5	0	0	0	0	0	5	5	25	0	30
N2E5	0.2-1.2	107	12.00	0	0	5	10	0	0	10	5	0	0	0	5	0	0	5	15	0	5
N2E6	1.2-2.2	107	12.00	5	0	5	5	0	0	5	10	0	0	0	0	0	0	0	0	0	0
N2E7	0.2-1.2	107	12.00	0	0	5	5	5	0	10	5	0	0	0	5	0	5	0	20	0	5
N2E8	1.2-2.2	107	12.00	5	0	0	10	0	0	5	5	0	0	0	0	0	0	0	30	0	5
N2E9	0.2-1.2	107	12.00	5	0	0	5	0	0	10	10	0	0	0	5	0	0	5	15	0	5
N2E10	1.2-2.2	107	12.00	5	0	0	5	0	0	0	10	0	0	0	0	0	0	0	40	0	5
N2E11	0.2-1.2	107	12.00	5	5	0	0	0	0	5	10	0	0	0	0	0	5	0	10	0	10
N2E12	1.2-2.2	107	12.00	5	0	0	5	0	0	5	5	0	5	0	0	0	5	0	10	0	35
N2S1	0.2-1.2	190	54.00	5	0	20	10	0	0	20	10	0	0	0	0	0	0	0	10	0	0
N2S2	1.2-2.2	190	54.00	0	0	20	10	0	0	30	0	0	0	0	15	0	0	0	20	0	0
N2S3	0.2-1.2	190	54.00	0	0	50	0	0	0	0	5	5	0	0	0	0	0	0	20	0	0
N2S4	1.2-2.2	190	54.00	0	0	70	0	0	0	0	0	0	0	0	10	0	0	0	15	0	0
N2S5	0.2-1.2	190	54.00	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0
N2S6	0.2-1.2	190	54.00	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0
N2S7	0.2-1.2	190	54.00	5	0	45	0	0	0	0	5	0	0	0	0	0	0	0	30	0	0
N2S8	1.2-2.2	190	54.00	5	0	80	0	0	0	0	5	0	0	0	5	0	0	0	10	0	0
N2S9	0.2-1.2	190	45.00	5	0	40	0	0	0	0	5	0	0	0	5	0	0	0	30	0	0
N2S10	1.2-2.2	190	45.00	0	0	50	0	0	0	0	10	0	0	0	0	0	0	0	20	0	0
N2S11	0.2-1.2	190	24.00	5	0	50	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0
N2S12	0.2-1.2	190	45.00	0	0	20	5	0	0	10	0	0	0	0	5	0	0	5	40	0	5
N2S13	0.2-1.2	190	45.00	5	0	20	10	0	0	5	0	0	0	0	10	0	0	5	30	0	5
N2S14	1.2-2.2	190	45.00	0	0	10	0	0	0	5	0	0	0	0	15	0	0	5	50	0	5
N2S15	0.2-1.2	190	54.00	5	0	5	5	5	0	5	10	0	0	0	10	0	0	5	10	0	0
N2S16	0.2-1.2	190	54.00	5	0	0	5	0	0	10	5	0	0	0	5	0	0	5	15	0	0
N2S17	1.2-2.2	190	54.00	5	0	25	0	15	10	25	0	0	0	0	5	0	0	5	5	0	5
N2W1	0.2-1.2	282	28.13	0	0	5	5	5	0	10	10	5	0	0	0	0	5	0	15	0	10
N2W2	1.2-2.2	282	28.13	5	0	5	5	0	0	25	0	0	0	0	0	0	20	5	25	0	5
N2W3	0.2-1.2	282	22.50	0	0	0	5	0	0	10	20	5	0	0	0	0	0	0	20	0	15
N2W4	1.2-2.2	282	22.50	5	0	30	5	0	0	5	5	0	0	0	0	0	5	0	20	0	25
N2W5	0.2-1.2	282	15.00	5	0	0	0	5	0	10	5	5	0	0	0	0	0	0	10	0	25
N2W6	1.2-2.2	282	15.00	5	0	5	5	0	0	20	0	0	0	0	0	0	10	0	5	0	20
N2W7	0.2-1.2	282	11.25	0	0	10	10	0	0	10	5	5	0	0	5	0	5	0	15	0	5
N2W8	1.2-2.2	282	11.25	0	0	30	0	0	0	0	0	0	0	0	5	0	10	5	10	0	5
N2W9	0.2-1.2	282	16.88	0	0	35	0	0	0	0	5	0	0	0	5	0	0	0	30	0	5
N2W10	1.2-2.2	282	16.88	0	0	50	0	0	0	0	5	0	0	0	5	0	0	0	20	0	5
N2W11	0.2-1.2	282	16.88	5	0	35	0	0	0	0	5	0	0	0	0	0	0	0	25	0	0
N2W12	1.2-2.2	282	16.88	5	0	70	0	0	0	0	0	0	0	0	0	0	0	0	15	0	5
N3N1	0.2-1.2	11	15.00	5	0	5	10	0	0	5	5	0	0	0	5	5	5	5	5	0	20
N3N2	1.2-2.2	11	15.00	5	0	0	10	0	0	5	5	0	0	0	5	0	0	5	15	5	25
N3N3	0.2-1.2	11	15.00	5	0	5	10	0	0	5	5	5	0	0	5	0	5	0	15	0	25
N3N4	0.2-1.2	11	15.00	5	0	5	5	0	0	10	5	5	0	5	0	0	5	0	15	0	10
N3N5	1.2-2.2	11	15.00	5	0	0	5	0	0	0	0	0	0	5	0	0	0	0	20	0	10
N3N6	0.2-1.2	11	15.00	5	0	5	5	0	0	0	5	0	0	0	0	0	0	0	15	10	30
N3N7	0.2-1.2	11	15.00	10	0	5	10	0	0	5	5	0	5	5	0	0	5	0	15	0	10
N3N8	0.2-1.2	11	12.00	5	0	15	10	5	0	5	5	5	0	0	0	0	0	5	10	0	10
N3N9	1.2-2.2	11	12.00	5	0	5	5	0	0	5	5	0	0	5	0	0	5	5	10	0	5
N3E1	0.2-1.2	102	10.13	5	0	0	5	0	0	5	5	0	0	5	0	0	0	0	10	0	10
N3E2	1.2-2.2	102	10.13	5	0	0	5	0	0	0	5	5	0	0	0	0	0	0	5	0	5
N3E3	0.2-1.2	102	10.13	10	0	0	10	5	0	5	10	0	0	0	0	0	0	0	10	5	5
N3E4	0.2-1.2	102	10.13	5	0	5	10	0	0	10	15	0	0	0	0	0	0	0	10	5	5
N3E5	1.2-2.2	102	10.13	5	0	0	5	5	0	0	5	0	0	0	0	0	0	0	10	0	0
N3S1	0.2-1.2	190	27.00	5	0	5	10	0	0	5	10	0	0	0	5	0	0	5	25	0	0

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
N3S2	1.2-2.2	190	27.00	5	0	5	0	0	0	0	5	5	0	5	5	0	0	0	20	0	0
N3S3	0.2-1.2	190	27.00	5	0	5	5	0	0	0	5	0	0	0	5	0	0	0	20	0	20
N3S4	0.2-1.2	190	27.00	10	0	5	10	0	0	5	5	0	0	0	5	0	0	0	15	0	20
N3S5	1.2-2.2	190	27.00	10	5	0	10	0	0	0	10	0	0	0	10	0	0	0	30	0	0
N3W1	0.2-1.2	280	17.10	5	0	0	5	0	0	0	5	0	0	0	5	0	0	5	20	0	5
N3W2	1.2-2.2	280	17.10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	5	25	0	5
N4N1	0.2-1.2	358	5.40	0	0	10	10	5	0	5	5	0	5	0	5	0	5	0	25	0	15
N4N2	1.2-2.2	358	5.40	5	0	5	10	5	0	5	5	0	0	5	5	0	0	0	50	0	5
N4N3	0.2-1.2	358	5.40	5	0	0	10	0	5	0	0	0	0	0	5	0	5	0	55	0	10
N4N4	1.2-2.2	358	5.40	5	0	5	5	0	0	10	10	0	0	0	5	0	0	0	60	0	0
N4N5	0.2-1.2	358	12.15	0	0	0	5	5	0	5	5	0	0	0	10	0	0	0	60	0	5
N4N6	0.2-1.2	358	16.20	5	0	0	5	0	0	10	5	0	0	0	15	0	0	0	55	0	10
N4N7	0.2-1.2	358	12.15	5	0	0	5	0	0	5	5	0	0	0	5	0	0	0	55	0	5
N4N8	1.2-2.2	358	12.15	5	0	0	10	0	0	5	10	0	0	0	5	0	0	0	60	0	10
N4N9	0.2-1.2	358	12.15	5	0	0	5	0	0	5	5	0	0	5	5	0	0	0	40	0	0
N4N10	1.2-2.2	358	12.15	5	0	5	5	0	0	10	15	0	0	0	5	0	0	0	50	0	10
N4N11	0.2-1.2	358	5.40	5	0	0	10	0	0	5	5	5	0	0	0	0	0	0	45	0	15
N4N12	1.2-2.2	358	5.40	5	0	0	5	0	0	5	10	0	0	0	0	0	0	0	60	0	0
N4N13	0.2-1.2	358	5.40	0	0	0	5	5	0	10	5	0	0	0	5	0	0	0	40	0	20
N4N14	1.2-2.2	358	5.40	5	0	0	5	0	0	5	0	0	0	0	0	0	0	0	70	0	0
N4E1	0.2-1.2	83	13.50	5	0	0	10	10	0	10	5	0	0	0	10	0	0	5	10	0	10
N4E2	1.2-2.2	83	13.50	5	0	0	5	5	0	10	10	0	0	0	5	0	0	5	20	0	5
N4E3	0.2-1.2	83	4.50	5	0	0	5	5	0	10	5	0	0	5	10	0	0	0	25	0	0
N4E4	1.2-2.2	83	13.50	5	0	0	5	5	0	10	0	0	0	0	15	0	0	0	40	0	5
N4E5	1.2-2.2	83	3.00	5	0	5	5	0	0	5	0	0	0	0	10	0	0	5	10	0	0
N4E6	0.2-1.2	83	6.00	10	0	5	0	0	0	0	5	0	0	0	0	0	5	0	40	0	5
N4E7	1.2-2.2	83	6.00	5	0	0	5	5	0	10	0	0	0	0	5	0	5	5	20	0	5
N4E8	0.2-1.2	83	6.00	10	0	5	5	0	0	0	5	0	0	0	5	0	0	0	35	0	20
N4E9	1.2-2.2	83	6.00	5	0	5	10	0	0	5	5	0	0	0	10	0	0	0	45	0	0
N4E10	0.2-1.2	83	6.00	10	0	0	10	0	0	5	5	0	0	0	5	0	0	0	30	0	5
N4E11	1.2-2.2	83	6.00	10	0	5	5	0	0	10	0	0	0	0	5	0	5	5	25	0	0
N4S1	0.2-1.2	178	18.00	5	0	5	5	5	0	10	10	0	0	0	10	0	0	0	20	0	5
N4S2	1.2-2.2	178	18.00	5	0	5	5	5	0	5	10	0	0	0	10	0	0	0	30	0	0
N4S3	0.2-1.2	178	18.00	5	0	5	10	0	0	5	0	0	0	0	15	0	0	0	40	0	5
N4S4	0.2-1.2	178	27.00	5	0	0	5	0	0	0	5	0	0	0	10	0	0	0	60	0	5
N4S5	0.2-1.2	178	27.00	5	0	0	5	0	5	5	0	0	0	0	10	0	0	5	70	0	5
N4S6	1.2-2.2	178	27.00	5	0	5	5	0	0	5	0	0	0	0	5	0	0	5	55	0	0
N4S7	0.2-1.2	178	27.00	5	0	0	5	0	0	5	0	0	0	0	10	0	0	0	60	0	10
N4S8	1.2-2.2	178	27.00	5	0	10	5	5	0	0	0	0	0	0	10	0	0	5	50	0	0
N4S9	0.2-1.2	178	27.00	5	0	0	5	0	0	5	5	0	0	0	10	0	0	0	70	0	5
N4S10	0.2-1.2	178	24.00	5	0	0	5	5	0	5	5	0	0	0	10	0	0	5	40	0	10
N4S11	1.2-2.2	178	24.00	5	0	0	5	10	0	0	5	0	0	0	10	0	0	5	30	0	0
N4S12	0.2-1.2	178	24.00	5	0	0	10	0	0	5	10	0	0	0	10	0	0	0	50	5	10
N4S13	1.2-2.2	178	24.00	5	0	0	5	5	0	10	0	0	0	0	15	0	0	0	50	0	0
N4S14	0.2-1.2	178	24.00	5	0	0	5	5	0	10	5	0	0	0	5	0	5	5	15	0	5
N4S15	1.2-2.2	178	24.00	5	0	0	5	5	0	10	0	0	0	0	10	0	0	10	40	0	0
N4S16	0.2-1.2	178	36.00	5	0	0	5	5	0	5	5	0	0	0	10	0	5	5	30	0	10
N4W1	0.2-1.2	264	11.25	5	0	0	5	0	0	5	10	0	0	0	5	0	0	5	45	0	0
N4W2	1.2-2.2	264	11.25	5	0	0	5	5	0	5	5	0	0	0	10	0	0	0	60	0	0
N4W3	0.2-1.2	264	7.50	10	0	0	5	10	0	5	5	0	0	0	5	0	0	0	40	0	0
N4W4	1.2-2.2	264	11.25	5	0	5	5	5	0	5	5	0	0	0	10	0	0	0	35	0	0
N4W5	0.2-1.2	264	3.75	10	0	0	5	5	0	5	5	0	0	0	15	0	0	0	45	0	5
N4W6	1.2-2.2	264	7.50	5	0	5	5	5	0	5	5	0	0	0	10	0	0	0	55	0	0
N4W7	0.2-1.2	264	11.25	5	0	5	5	5	0	5	5	0	0	0	10	0	0	5	40	0	5
N4W8	1.2-2.2	264	11.25	5	0	0	5	10	0	5	5	0	0	0	15	0	0	5	50	0	0
N4W9	0.2-1.2	264	22.50	10	0	0	5	10	0	0	5	0	0	0	5	0	0	0	25	0	15
N4W10	1.2-2.2	264	22.50	5	0	0	5	5	0	10	0	0	0	0	10	0	5	5	25	0	5
N5N1	0.2-1.2	345	8.10	5	0	0	10	10	0	10	5	5	0	0	10	0	5	0	5	5	5
N5N2	1.2-2.2	345	8.10	5	0	0	5	5	5	5	5	0	0	0	5	0	10	0	20	0	10
N5N3	0.2-1.2	345	5.40	0	0	0	5	5	0	10	5	0	0	0	5	0	0	5	20	5	10
N5N4	1.2-2.2	345	5.40	5	0	0	5	0	0	5	5	0	0	0	5	0	0	5	40	0	5
N5N5	0.2-1.2	345	8.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N5N6	1.2-2.2	345	8.10	5	0	0	5	0	0	0	5	0	0	0	10	0	0	0	30	0	5
N5N7	0.2-1.2	345	8.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N5N8	1.2-2.2	345	8.10	5	0	0	5	0	0	5	5	0	0	0	10	0	5	0	30	0	5
N5N9	0.2-1.2	345	4.05	0	0	0	15	10	0	10	15	10	0	10	0	0	0	0	20	5	10
N5N10	0.2-1.2	345	8.10	5	0	0	10	0	0	5	5	0	0	0	0	0	0	0	10	0	0
N5N11	1.2-2.2	345	8.10	0	0	0	5	0	0	5	0	0	0	0	0	0	0	0	15	0	0
N5N12	0.2-1.2	345	16.20	5	0	0	10	10	0	10	5	5	0	0	5	0	0	0	15	5	0
N5N13	0.2-1.2	345	16.20	0	0	0	5	5	0	10	5	0	0	5	5	0	0	0	20	5	0
N5N14	1.2-2.2	345	20.25	0	0	0	5	0	0	5	5	0	0	0	5	0	0	0	30	5	0
N5N15	0.2-1.2	345	12.15	5	0	0	10	5	0	10	5	0	0	0	5	0	0	0	30	5	0
N5N16	0.2-1.2	345	16.20	5	0	0	5	0	0	5	5	0	0	0	5	0	0	0	50	5	0
N5N17	1.2-2.2	345	16.20	0	0	0	5	0	0	5	5	0	0	5	5	0	0	0	35	5	0

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
N5E1	0.2-1.2	76	9.00	5	0	0	10	0	0	5	5	0	0	0	5	0	0	0	50	5	0
N5E2	1.2-2.2	76	9.00	0	0	10	5	5	0	5	5	0	0	0	0	0	0	5	50	0	0
N5E3	0.2-1.2	76	6.00	5	0	5	10	0	0	10	5	0	0	0	5	0	0	5	15	5	5
N5E4	1.2-2.2	76	6.00	5	0	0	5	5	0	5	0	0	0	5	5	0	0	5	60	0	5
N5E5	0.2-1.2	76	6.00	5	0	5	10	5	0	10	0	0	0	5	5	0	0	5	20	5	5
N5E6	1.2-2.2	76	6.00	5	0	0	5	5	0	5	0	0	0	0	5	0	5	0	50	0	5
N5E7	0.2-1.2	76	9.00	5	0	0	10	5	5	5	5	0	0	0	5	0	0	0	45	0	0
N5E8	0.2-1.2	76	4.50	0	0	0	5	0	0	5	5	0	0	0	5	0	5	0	5	5	5
N5E9	0.2-1.2	76	13.50	5	0	0	5	0	0	5	0	0	0	0	5	0	0	5	10	0	0
N5S1	0.2-1.2	156	23.96	5	0	0	5	0	5	5	5	0	0	0	5	0	0	0	40	0	0
N5S2	1.2-2.2	156	23.96	5	0	0	5	0	0	5	5	0	0	0	5	0	0	0	60	0	0
N5S3	0.2-1.2	156	15.98	5	0	0	5	5	0	5	5	0	0	0	5	0	0	0	50	0	0
N5S4	1.2-2.2	156	15.98	5	0	0	5	0	0	5	5	0	0	0	5	0	0	0	60	0	0
N5S5	0.2-1.2	156	15.98	5	0	0	5	0	0	5	5	0	0	0	10	0	0	0	50	0	0
N5S6	0.2-1.2	156	7.99	10	0	0	5	0	0	5	5	0	0	0	5	0	0	0	50	0	0
N5S7	1.2-2.2	156	7.99	5	0	0	5	5	0	0	10	0	0	0	5	0	0	0	50	0	0
N5S8	0.2-1.2	156	15.98	10	0	0	5	0	0	5	5	0	0	5	5	0	0	5	55	0	0
N5S9	0.2-1.2	156	15.98	5	0	0	5	5	0	5	5	0	0	0	5	0	0	0	40	0	0
N5S10	1.2-2.2	156	15.98	5	0	0	5	0	0	0	5	0	0	0	5	0	0	0	60	0	0
N5S11	0.2-1.2	156	10.65	5	0	20	0	0	0	0	5	0	0	0	5	0	0	0	50	0	0
N5S12	1.2-2.2	156	10.65	5	0	0	0	0	0	0	10	0	0	0	0	0	0	0	70	0	0
N5S13	1.2-2.2	156	10.65	5	0	15	5	0	0	0	5	0	0	0	5	0	0	0	50	0	5
N5S14	0.2-1.2	156	15.98	5	0	0	5	0	0	5	5	5	0	0	10	0	0	0	20	5	0
N5S15	1.2-2.2	156	15.98	10	0	0	5	5	0	0	5	0	0	0	10	0	0	0	60	0	5
N5S16	0.2-1.2	156	15.98	0	0	0	5	5	0	5	15	5	0	0	5	0	0	0	30	5	5
N5S17	1.2-2.2	156	15.98	10	0	0	5	5	0	0	0	0	0	0	10	0	0	0	60	0	0
N5W1	0.2-1.2	270	22.50	5	0	0	5	0	0	0	0	0	0	0	5	0	0	5	50	0	0
N5W2	0.2-1.2	270	22.50	5	0	0	5	0	0	5	5	0	0	0	0	0	0	5	45	0	5
S1N1	0.2-1.2	20	13.50	0	0	0	5	0	0	15	0	0	5	0	0	0	5	0	5	0	45
S1N2	0.2-1.2	20	9.00	5	0	0	10	0	0	20	0	0	20	5	0	0	5	0	0	0	30
S1N3	1.2-2.2	20	9.00	5	0	0	0	0	0	5	0	0	5	5	0	0	5	0	10	0	25
S1N4	0.2-1.2	20	9.00	5	0	0	5	5	5	15	10	0	5	0	0	0	5	0	5	0	15
S1N5	1.2-2.2	20	9.00	0	0	0	5	0	0	0	0	0	5	0	0	0	5	0	15	0	35
S1N6	0.2-1.2	20	12.00	5	0	0	10	5	0	5	10	5	5	5	0	0	5	5	5	0	15
S1N7	0.2-1.2	20	12.00	0	0	0	10	0	0	10	5	10	10	0	0	0	5	0	5	0	20
S1N8	1.2-2.2	20	12.00	5	0	0	5	5	0	5	0	0	5	5	0	0	5	0	10	0	30
S1N9	0.2-1.2	20	13.50	0	0	0	10	5	0	20	5	5	15	0	0	0	10	0	5	0	25
S1N10	0.2-1.2	20	9.00	0	0	0	10	0	0	15	15	5	5	0	0	0	5	0	10	0	5
S1N11	1.2-2.2	20	9.00	5	0	0	15	0	0	15	10	5	5	5	5	0	0	0	5	0	5
S1N12	0.2-1.2	20	13.50	5	0	0	5	0	0	15	5	5	5	0	0	0	0	0	5	0	15
S1N13	1.2-2.2	20	13.50	5	0	0	5	0	0	10	5	0	5	10	0	0	0	5	5	0	15
S1N14	0.2-1.2	20	13.50	0	0	0	5	0	0	5	10	5	5	0	0	0	5	0	5	0	70
S1N15	0.2-1.2	20	13.50	5	0	0	5	0	0	5	5	5	10	0	0	0	5	0	5	0	40
S1N16	1.2-2.2	20	13.50	5	0	10	5	0	0	5	5	0	5	0	0	0	5	0	10	0	10
S1E1	0.2-1.2	113	19.24	0	0	0	5	5	0	10	5	5	5	5	0	0	5	5	5	0	25
S1E2	1.2-2.2	113	19.24	5	0	0	5	0	0	5	0	0	5	5	0	0	5	0	0	0	70
S1E3	0.2-1.2	113	25.65	0	0	0	5	0	0	10	5	5	15	5	0	0	5	0	10	0	25
S1E4	1.2-2.2	113	25.65	5	0	0	5	5	5	5	0	0	15	0	0	0	0	0	0	0	65
S1E5	0.2-1.2	113	12.83	0	0	0	5	0	0	10	10	0	10	0	0	0	5	0	5	0	25
S1E6	1.2-2.2	113	12.83	0	0	0	10	5	0	10	5	0	5	0	0	0	0	0	5	0	45
S1E7	0.2-1.2	113	12.83	0	0	0	5	5	0	20	10	0	10	0	0	0	5	0	5	0	25
S1E8	0.2-1.2	113	19.24	0	0	0	5	0	0	20	0	0	5	10	0	0	5	5	0	0	40
S1E9	1.2-2.2	113	19.24	5	0	0	5	0	0	5	0	0	5	0	0	0	5	0	0	0	60
S1E10	0.2-1.2	113	4.28	5	0	0	5	0	0	5	5	0	5	5	0	0	5	0	5	0	40
S1S1	0.2-1.2	198	30.38	5	0	0	5	0	0	0	0	0	0	5	0	0	0	5	0	0	35
S1S2	1.2-2.2	198	30.38	5	0	0	0	0	0	0	0	0	5	0	0	0	0	0	5	0	25
S1S3	0.2-1.2	198	40.50	10	0	0	0	0	0	0	0	0	5	0	0	0	20	0	0	0	0
S1S4	0.2-1.2	198	40.50	5	0	0	5	0	0	10	0	0	5	5	0	0	0	0	5	0	25
S1S5	1.2-2.2	198	40.50	0	0	0	0	0	0	5	0	0	5	0	0	0	0	0	10	0	25
S1S6	0.2-1.2	198	40.50	0	0	0	5	0	0	0	0	0	0	0	0	0	5	0	0	0	15
S1S7	0.2-1.2	198	40.50	10	0	0	5	0	0	0	0	0	5	0	0	0	5	0	0	0	35
S1S8	1.2-2.2	198	40.50	5	0	0	5	0	0	5	0	0	5	0	0	0	5	5	5	0	40
S1S9	0.2-1.2	198	40.50	5	0	0	5	0	0	5	0	0	5	5	0	0	5	0	0	0	40
S1S10	1.2-2.2	198	40.50	5	0	0	5	0	0	5	0	0	5	0	0	0	5	5	10	0	20
S1S11	0.2-1.2	198	30.38	10	0	0	5	0	0	5	0	0	10	5	0	0	5	0	10	0	35
S1S12	1.2-2.2	198	30.38	10	0	0	5	10	0	10	0	0	5	5	0	0	5	5	10	0	40
S1S13	0.2-1.2	198	20.25	5	0	0	5	10	0	15	0	0	10	5	0	0	5	0	0	0	0
S1S14	1.2-2.2	198	20.25	5	0	0	0	5	0	0	0	0	0	0	0	0	5	0	10	0	50
S1S15	0.2-1.2	198	6.75	25	0	0	5	0	0	5	0	0	5	0	0	0	5	0	5	0	30
S1S16	0.2-1.2	198	6.75	5	0	0	5	0	0	10	0	0	0	0	0	0	15	0	0	0	25
S1S17	1.2-2.2	198	6.75	5	0	0	0	0	0	0	0	0	0	0	5	0	10	0	5	0	40
S1W1	0.2-1.2	296	5.06	5	0	0	5	0	0	0	5	5	5	0	0	0	0	0	5	0	15
S1W2	1.2-2.2	296	5.06	5	0	0	0	0	0	5	0	0	0	5	0	0	5	0	10	0	45
S1W3	0.2-1.2	296	5.06	5	0	0	5	0	0	5	5	5	0	5	0	0	0	0	5	0	55

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
S1W4	1.2-2.2	296	5.06	5	0	0	0	0	0	0	0	0	5	5	0	0	0	0	5	0	55
S1W5	0.2-1.2	296	20.25	0	0	0	0	0	0	5	10	0	5	5	0	0	5	5	5	0	35
S1W6	1.2-2.2	296	20.25	5	0	0	0	10	0	0	0	0	5	0	0	0	5	0	5	0	50
S1W7	0.2-1.2	296	20.25	5	0	0	0	0	0	10	0	5	5	5	5	0	5	0	5	0	25
S1W8	1.2-2.2	296	15.19	10	0	0	0	0	5	10	0	0	15	5	0	0	0	0	10	0	0
S1W9	0.2-1.2	296	15.19	5	0	0	5	10	0	5	0	0	5	5	5	0	5	0	5	0	15
S1W10	1.2-2.2	296	15.19	5	0	0	5	5	0	5	0	5	5	5	0	0	0	0	10	0	15
S2N1	0.2-1.2	2	13.50	5	0	0	5	0	0	15	5	5	0	0	0	0	5	10	0	0	25
S2N2	1.2-2.2	2	13.50	5	0	5	5	0	0	10	0	10	5	0	0	0	5	5	0	0	10
S2N3	0.2-1.2	2	13.50	5	0	5	5	10	5	5	0	5	0	0	0	0	5	10	0	0	25
S2N4	1.2-2.2	2	13.50	10	0	0	5	0	0	10	0	0	0	0	0	0	10	5	5	0	40
S2N5	0.2-1.2	2	18.00	5	0	0	10	0	0	10	10	0	0	5	5	0	0	5	10	0	0
S2N6	0.2-1.2	2	12.00	5	0	0	10	0	0	10	5	5	20	0	0	0	10	0	0	0	20
S2N7	1.2-2.2	2	12.00	5	0	0	5	10	0	15	0	0	0	0	0	0	10	15	0	0	30
S2N8	0.2-1.2	2	3.00	0	0	0	10	0	0	5	0	5	5	0	0	0	15	5	0	0	20
S2N9	0.2-1.2	2	12.00	5	0	0	5	0	0	5	25	25	0	0	0	0	5	5	5	0	20
S2N10	0.2-1.2	2	9.00	5	0	5	10	5	0	10	0	0	5	5	0	0	5	5	0	0	35
S2N11	1.2-2.2	2	9.00	10	0	0	15	0	0	20	0	0	0	0	0	0	10	5	0	0	30
S2N12	0.2-1.2	2	9.00	0	0	10	10	0	0	50	0	0	0	0	0	0	10	0	0	0	15
S2N13	1.2-2.2	2	9.00	5	0	5	5	10	0	10	0	0	0	10	0	0	0	5	0	0	10
S2N14	0.2-1.2	2	9.00	15	0	5	10	0	0	15	0	5	5	0	0	0	25	0	5	0	20
S1N15	1.2-2.2	2	9.00	5	0	5	5	0	0	15	5	0	0	0	0	0	5	5	0	0	5
S2E1	0.2-1.2	93	10.13	10	0	0	5	0	0	5	5	5	5	0	0	0	0	0	5	0	20
S2E2	1.2-2.2	93	5.06	5	0	0	0	5	0	5	5	0	5	5	0	0	0	5	5	0	15
S2E3	0.2-1.2	93	5.06	15	0	0	5	5	0	15	5	10	0	0	5	0	5	5	10	0	20
S2E4	0.2-1.2	93	15.19	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	20
S2E5	1.2-2.2	93	20.25	5	0	0	0	0	0	5	0	0	0	0	0	0	5	0	0	0	70
S2E6	0.2-1.2	93	6.75	0	0	0	5	5	10	5	5	5	5	0	0	0	0	5	5	0	10
S2E7	1.2-2.2	93	6.75	5	0	0	5	10	0	5	5	0	5	5	0	0	5	5	0	0	20
S2E8	0.2-1.2	93	10.13	0	0	0	5	5	0	0	0	5	0	0	0	0	5	10	5	0	0
S2E9	1.2-2.2	93	10.13	5	0	0	5	0	0	10	5	0	5	0	0	0	5	5	10	0	20
S2E10	0.2-1.2	93	10.13	5	0	20	10	15	0	5	5	5	0	0	0	0	5	5	0	0	5
S2E11	1.2-2.2	93	10.13	5	0	5	5	5	0	10	5	0	0	5	0	0	5	5	0	0	25
S2S1	0.2-1.2	182	20.25	10	0	0	0	10	5	20	0	0	0	0	0	0	0	5	10	0	40
S2S2	1.2-2.2	182	20.25	5	0	0	0	0	0	25	5	0	0	0	0	0	5	5	10	5	10
S2S3	0.2-1.2	182	20.25	10	0	0	5	0	0	30	5	0	0	0	0	0	0	5	5	0	40
S2S4	1.2-2.2	182	20.25	10	0	0	5	0	0	20	5	0	5	0	0	0	5	10	5	0	5
S2S5	0.2-1.2	182	27.00	0	0	0	10	0	0	15	15	15	0	0	0	0	0	5	5	0	0
S2S6	1.2-2.2	182	27.00	5	5	5	0	5	0	5	10	5	0	0	0	0	0	0	5	0	5
S2S7	0.2-1.2	182	6.75	5	0	0	5	0	0	5	10	0	5	5	5	0	0	5	0	0	10
S2S8	1.2-2.2	182	13.50	10	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5	0	20
S2S9	0.2-1.2	182	13.50	30	0	0	5	0	5	10	10	0	0	0	5	0	0	5	40	0	0
S2S10	0.2-1.2	182	20.25	20	0	5	0	0	0	10	10	0	0	0	5	0	0	0	20	0	5
S2S11	0.2-1.2	182	20.25	15	0	0	5	0	0	5	10	0	0	0	0	0	0	0	30	0	0
S2S12	1.2-2.2	182	20.25	10	0	0	5	0	0	5	0	5	0	0	5	0	0	0	15	0	10
S2S13	0.2-1.2	182	6.75	5	0	0	5	0	0	5	0	5	0	5	0	5	0	0	5	0	5
S2S14	0.2-1.2	182	20.25	0	0	0	0	5	5	5	0	0	0	0	0	0	10	0	0	0	60
S2S15	1.2-2.2	182	20.25	5	0	0	0	0	0	0	5	0	5	0	0	0	0	0	5	0	50
S2W1	0.2-1.2	268	19.24	10	0	0	5	0	0	5	5	0	0	0	0	0	10	5	5	0	45
S2W2	1.2-2.2	268	19.24	5	0	0	5	0	5	5	0	0	0	0	0	0	10	0	0	0	40
S2W3	0.2-1.2	268	8.55	20	0	0	5	0	0	20	10	0	0	0	5	0	0	0	5	0	0
S2W4	0.2-1.2	268	17.10	5	0	5	0	0	0	15	15	5	0	0	0	0	0	0	15	0	0
S2W5	1.2-2.2	268	17.10	5	0	20	5	0	0	5	5	0	0	0	5	0	5	5	5	0	5
S2W6	0.2-1.2	268	12.83	5	0	0	15	10	0	15	10	5	0	0	0	0	0	0	10	0	5
S2W7	1.2-2.2	268	12.83	5	0	5	5	5	5	5	10	0	0	0	5	0	5	5	10	0	5
S2W8	0.2-1.2	268	17.10	10	0	0	5	0	0	5	10	0	0	0	0	0	0	5	40	0	0
S2W9	0.2-1.2	268	12.83	15	5	0	5	0	0	5	10	10	5	5	0	0	0	0	15	0	0
S2W10	1.2-2.2	268	12.83	5	0	0	5	0	0	15	10	0	0	5	0	0	0	5	10	0	10
S2W11	0.2-1.2	268	12.83	5	0	0	5	0	0	10	10	0	5	0	0	0	0	5	5	0	5
S2W12	1.2-2.2	268	12.83	10	0	5	5	0	0	5	5	5	0	0	0	0	0	5	0	0	0
S3N1	0.2-1.2	358	4.50	5	0	15	5	0	0	0	0	0	5	0	0	0	0	0	0	0	25
S3N2	1.2-2.2	358	4.50	5	0	10	5	0	0	5	0	0	5	0	0	0	0	0	0	0	35
S3N3	0.2-1.2	358	4.50	5	0	30	5	0	0	0	0	0	0	0	0	0	0	0	5	0	30
S3N4	0.2-1.2	358	3.00	5	0	0	5	0	0	0	0	0	5	0	0	0	0	0	0	5	60
S3N5	0.2-1.2	358	9.00	10	0	20	10	0	0	5	0	0	0	0	0	0	5	0	0	0	35
S3N6	1.2-2.2	358	3.00	5	0	15	5	0	0	0	0	0	5	0	0	0	5	0	5	0	30
S3E1	0.2-1.2	92	10.13	5	0	5	5	0	0	5	0	0	0	0	0	0	0	0	5	0	30
S3E2	1.2-2.2	92	10.13	5	0	5	5	0	0	10	0	0	0	0	0	0	5	0	5	0	50
S3E3	0.2-1.2	92	6.75	5	0	0	10	5	0	5	5	0	0	5	5	0	0	0	15	0	10
S3E4	0.2-1.2	92	3.38	5	0	5	5	0	0	0	5	0	0	0	0	0	0	0	10	0	15
S3E5	1.2-2.2	92	3.38	5	0	0	10	0	0	5	0	0	5	5	0	0	0	0	5	0	25
S3E6	0.2-1.2	92	13.50	5	0	5	5	0	0	10	0	0	0	0	0	0	0	10	5	5	0	10
S3S1	0.2-1.2	188	27.00	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	15	0	10
S3S2	1.2-2.2	188	27.00	5	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	20	0	5

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
S3S3	0.2-1.2	188	20.25	10	0	0	5	0	0	0	5	0	0	0	0	0	0	5	25	0	0
S3S4	1.2-2.2	188	27.00	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0
S3S5	0.2-1.2	188	20.25	5	0	0	0	0	0	5	0	0	0	0	0	0	0	0	25	0	15
S3S6	0.2-1.2	188	20.25	5	0	0	5	0	0	5	5	0	5	0	0	0	0	5	15	0	15
S3W1	0.2-1.2	254	6.00	10	0	0	10	0	0	5	0	5	5	0	0	0	5	0	0	0	30
S3W2	1.2-2.2	254	6.00	5	0	10	5	0	0	10	5	0	0	5	5	0	0	5	5	0	10
S3W3	0.2-1.2	254	6.00	5	0	10	5	40	0	10	5	0	0	0	5	0	0	5	5	0	5
S3W4	1.2-2.2	254	6.00	5	0	10	5	40	0	10	5	0	0	0	5	0	0	5	5	0	5
S3W5	0.2-1.2	254	6.00	5	0	30	10	0	0	5	5	0	0	5	0	0	0	0	10	0	5
S3W6	1.2-2.2	254	6.00	5	0	35	5	0	0	0	0	0	0	0	0	0	5	0	10	0	10
S4N1	0.2-1.2	25	22.50	10	0	0	5	0	5	5	5	0	0	5	0	0	0	0	10	5	25
S4N2	1.2-2.2	25	22.50	10	5	5	5	0	0	10	0	0	0	0	0	0	10	0	5	0	40
S4N3	0.2-1.2	25	18.00	5	5	5	5	0	0	5	10	0	0	5	0	0	5	0	0	0	35
S4N4	1.2-2.2	25	18.00	5	0	5	5	0	0	5	0	0	0	0	0	0	5	0	0	0	25
S4N5	0.2-1.2	25	6.00	15	0	0	5	0	0	5	0	0	5	0	0	0	0	0	0	0	35
S4N6	1.2-2.2	25	6.00	15	0	0	5	0	0	0	0	0	0	0	0	0	5	0	0	0	35
S4N7	0.2-1.2	25	9.00	5	0	0	5	0	0	5	0	0	0	0	0	0	5	5	0	0	50
S4N8	1.2-2.2	25	9.00	10	0	0	5	0	0	5	0	0	0	0	0	0	5	0	0	0	50
S4N9	0.2-1.2	25	22.50	5	0	5	5	0	0	5	0	0	5	0	0	0	5	5	0	5	15
S4N10	1.2-2.2	25	22.50	5	0	5	5	0	0	5	0	0	5	0	0	0	0	0	0	0	30
S4N11	0.2-1.2	25	13.50	5	0	5	5	0	5	10	0	0	0	0	0	0	10	0	0	0	25
S4N12	0.2-1.2	25	13.50	5	0	5	5	10	0	10	0	5	10	5	0	0	5	0	0	5	10
S4N13	1.2-2.2	25	13.50	5	0	5	5	5	0	5	0	0	5	0	0	0	10	0	0	0	15
S4N14	0.2-1.2	25	13.50	5	0	5	10	0	0	10	0	10	5	0	0	0	5	0	0	5	20
S4N15	1.2-2.2	25	18.00	5	0	5	5	0	10	10	0	0	0	0	0	0	10	0	0	0	20
S4E1	0.2-1.2	118	6.41	5	0	0	10	0	5	10	0	0	0	0	0	0	10	0	0	0	20
S4E2	1.2-2.2	118	12.83	5	0	0	0	0	0	5	0	0	0	0	0	0	10	5	0	0	15
S4E3	0.2-1.2	118	12.83	15	0	5	5	0	0	5	0	0	0	0	0	0	10	0	10	0	15
S4E4	1.2-2.2	118	12.83	5	0	5	5	0	0	5	0	0	0	0	0	0	5	5	0	0	20
S4E5	0.2-1.2	118	12.83	20	10	5	5	5	0	10	5	0	0	0	0	0	0	10	10	0	15
S4E6	1.2-2.2	118	12.83	10	0	0	0	0	0	5	0	0	0	0	0	0	5	5	0	0	50
S4E7	0.2-1.2	118	12.83	5	5	5	5	0	5	10	5	5	0	0	5	0	0	10	15	0	5
S4E8	0.2-1.2	118	12.83	5	5	5	5	0	0	0	0	0	0	5	0	0	5	10	10	0	20
S4E9	1.2-2.2	118	12.83	5	0	10	5	0	0	5	0	0	0	0	0	0	5	5	0	0	30
S4E10	0.2-1.2	118	19.24	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	30
S4E11	1.2-2.2	118	19.24	10	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	25
S4S1	0.2-1.2	206	40.50	15	0	5	5	10	0	5	0	0	5	0	0	0	5	5	0	0	10
S4S2	1.2-2.2	206	50.63	5	0	5	0	5	0	5	0	0	0	0	0	0	10	15	0	0	10
S4S3	0.2-1.2	206	40.50	5	0	40	5	5	0	10	0	0	0	0	0	0	5	5	0	0	5
S4S4	1.2-2.2	206	50.63	10	0	5	5	15	0	5	0	0	0	5	0	0	5	5	5	5	5
S4S5	0.2-1.2	206	20.25	10	0	0	0	0	10	5	0	0	0	0	0	0	5	5	5	0	15
S4S6	1.2-2.2	206	30.38	5	0	5	0	5	0	5	0	0	0	0	0	0	5	5	0	0	10
S4S7	0.2-1.2	206	30.38	5	0	5	5	10	0	0	0	0	0	5	0	0	5	5	0	0	5
S4S8	1.2-2.2	206	30.38	10	0	0	5	0	0	5	0	0	0	5	0	0	5	0	0	0	5
S4S9	0.2-1.2	206	30.38	5	0	0	5	15	0	0	0	0	0	5	0	0	5	10	0	0	5
S4S10	1.2-2.2	206	40.50	10	5	0	0	5	0	5	0	0	0	0	0	0	5	10	0	0	5
S4S11	0.2-1.2	206	40.50	10	0	0	0	5	5	0	0	0	0	0	0	0	5	5	5	0	5
S4S12	0.2-1.2	206	30.38	10	0	0	0	0	0	5	5	0	0	0	0	0	5	5	5	0	10
S4S13	0.2-1.2	206	30.38	5	0	0	5	0	0	0	5	0	0	0	0	0	0	5	0	10	0
S4S14	1.2-2.2	206	30.38	10	0	0	5	0	0	0	0	0	0	0	0	0	0	5	5	0	5
S4S15	0.2-1.2	206	30.38	5	5	0	0	5	0	5	0	0	0	0	0	0	5	5	5	0	25
S4W1	0.2-1.2	290	20.25	10	0	0	0	5	0	0	0	0	0	0	0	0	5	0	0	0	10
S4W2	1.2-2.2	290	20.25	15	0	0	0	0	0	5	0	0	0	0	0	0	5	0	0	0	10
S4W3	0.2-1.2	290	3.38	10	0	0	5	5	5	10	5	0	5	0	0	0	5	5	5	0	10
S4W4	1.2-2.2	290	10.13	5	0	5	5	10	5	5	0	0	5	0	5	0	5	0	5	0	5
S4W5	0.2-1.2	290	3.38	0	0	5	5	10	0	5	5	5	0	5	0	0	0	5	5	5	5
S4W6	1.2-2.2	290	10.13	5	0	10	10	5	0	5	0	5	0	0	0	0	5	5	5	0	10
S4W7	0.2-1.2	290	6.75	20	0	0	10	0	0	5	0	5	5	0	0	0	10	5	5	0	5
S4W8	1.2-2.2	290	10.13	10	0	0	5	10	0	5	0	0	5	0	5	0	10	5	10	0	5
S4W9	0.2-1.2	290	5.06	15	5	0	0	0	0	10	0	0	0	0	0	0	5	15	5	0	5
S4W10	1.2-2.2	290	5.06	10	0	0	5	0	0	5	0	0	0	0	0	0	0	15	0	0	5
S5N1	0.2-1.2	10	3.40	0	0	0	5	0	0	10	5	0	0	0	0	0	0	10	5	0	5
S5N2	1.2-2.2	10	3.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	15
S5N3	0.2-1.2	10	3.40	5	0	0	5	0	0	0	0	5	0	0	0	0	0	5	5	0	20
S5N4	0.2-1.2	10	3.40	0	0	0	5	0	0	0	0	0	0	0	0	0	5	5	5	0	10
S5N5	0.2-1.2	10	10.20	10	0	0	15	0	0	5	15	0	5	5	0	0	0	5	10	0	10
S5N6	1.2-2.2	10	10.20	10	0	0	15	0	0	5	20	0	0	0	0	0	5	0	10	0	25
S5N7	0.2-1.2	10	10.20	0	0	0	10	5	0	5	10	0	0	5	0	0	5	0	5	5	45
S5E1	0.2-1.2	98	7.65	5	0	5	10	0	0	10	15	0	0	5	0	0	5	0	10	0	10
S5E2	1.2-2.2	98	7.65	5	0	0	10	5	0	10	15	0	0	5	0	0	0	0	15	0	10
S5E3	0.2-1.2	98	11.48	20	0	0	15	0	0	10	10	0	5	5	0	0	0	0	10	5	10
S5E4	1.2-2.2	98	11.48	5	0	0	10	0	0	0	10	0	0	5	0	0	0	0	5	0	25
S5E5	0.2-1.2	98	11.48	5	0	0	10	0	0	5	20	0	0	5	0	0	0	0	20	0	5
S5E6	1.2-2.2	98	11.48	5	0	0	15	0	0	5	15	0	0	0	0	0	0	0	10	0	0

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
S5E7	0.2-1.2	98	5.74	5	0	0	5	0	0	10	10	5	5	5	0	0	0	0	5	0	50
S5E8	1.2-2.2	98	5.74	0	0	0	5	0	0	5	5	5	5	5	0	0	5	0	5	0	50
S5E9	0.2-1.2	98	7.65	5	0	0	0	0	0	0	0	0	5	0	0	0	0	5	5	0	65
S5E10	1.2-2.2	98	7.65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75
S5S1	0.2-1.2	182	45.90	10	0	0	5	0	0	5	15	0	0	10	0	0	0	0	10	0	10
S5S2	0.2-1.2	182	11.48	0	0	0	10	0	0	10	15	0	5	10	0	0	0	0	15	0	10
S5S3	1.2-2.2	182	11.48	0	0	0	10	0	0	10	25	0	0	0	0	0	0	0	20	0	5
S5S4	0.2-1.2	182	11.48	5	0	0	5	0	0	5	15	0	0	0	0	0	0	0	10	0	10
S5S5	1.2-2.2	182	11.48	15	0	0	5	0	0	5	15	0	0	0	0	0	0	0	10	0	10
S5S6	0.2-1.2	182	11.48	5	0	0	10	0	0	5	10	0	0	0	0	0	0	5	10	0	15
S5S7	1.2-2.2	182	11.48	15	0	0	10	0	0	10	10	0	0	0	0	0	0	0	10	0	25
S5S8	0.2-1.2	182	11.48	5	0	0	10	0	0	0	5	0	0	5	0	0	0	0	10	0	15
S5S9	1.2-2.2	182	11.48	5	0	0	0	0	0	0	0	0	5	0	0	0	0	0	5	0	25
S5S10	0.2-1.2	182	11.48	5	0	0	5	0	0	0	5	0	0	5	0	0	0	0	5	0	15
S5S11	1.2-2.2	182	11.48	10	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	50
S5S12	0.2-1.2	182	11.48	15	0	0	5	0	0	0	15	0	0	0	0	0	0	0	15	0	5
S5S13	0.2-1.2	182	22.95	0	0	0	5	0	0	10	25	0	0	0	0	0	0	5	15	0	5
S5S14	1.2-2.2	182	22.95	20	0	0	5	5	0	5	10	0	0	5	0	0	0	5	5	0	10
S5W1	0.2-1.2	276	9.69	0	0	0	10	0	0	5	30	0	0	10	0	0	0	0	20	0	5
S5W2	1.2-2.2	276	9.69	5	0	0	10	5	0	5	20	0	0	10	0	0	0	0	25	0	5
S5W3	1.2-2.2	276	9.69	5	0	0	5	5	0	5	25	0	0	5	0	0	0	5	25	0	0
S5W4	0.2-1.2	276	9.69	5	0	0	5	0	0	5	20	0	0	5	0	0	0	5	20	0	0
S5W5	1.2-2.2	276	9.69	5	0	0	10	0	0	0	15	0	0	5	0	0	0	0	20	0	5
S5W6	0.2-1.2	276	9.69	0	0	5	5	0	0	5	20	0	0	0	5	0	0	0	20	0	0
S5W7	1.2-2.2	276	9.69	0	0	0	10	0	0	5	25	0	0	10	0	0	0	0	25	0	0
S5W8	0.2-1.2	276	14.54	5	0	0	5	10	0	5	10	0	0	10	0	0	0	0	10	0	10
S5W9	1.2-2.2	276	14.54	5	0	0	10	0	0	5	10	0	5	5	0	0	0	5	10	0	10
S6N1	0.2-1.2	355	6.00	0	0	0	15	15	0	20	10	10	0	0	5	0	10	10	0	5	0
S6N2	1.2-2.2	355	6.00	10	0	0	10	5	0	5	0	0	0	0	10	0	20	10	10	0	20
S6N3	0.2-1.2	355	6.00	10	0	0	10	0	0	10	5	10	5	0	5	0	10	15	5	5	10
S6N4	1.2-2.2	355	6.00	5	0	5	10	10	0	20	5	0	0	0	10	0	5	5	10	0	5
S6N5	0.2-1.2	355	6.00	10	0	0	5	10	0	10	5	10	5	0	0	0	10	10	0	5	15
S6N6	1.2-2.2	355	6.00	15	0	10	5	5	0	10	0	0	0	0	5	0	10	5	5	0	30
S6N7	0.2-1.2	355	4.50	0	0	0	10	0	0	10	0	0	0	0	0	0	15	10	10	0	15
S6N8	1.2-2.2	355	4.50	10	0	5	5	5	0	10	5	0	0	0	5	0	10	10	0	0	10
S6N9	0.2-1.2	355	9.00	0	0	5	5	5	0	10	10	5	5	0	5	0	5	15	0	5	5
S6N10	1.2-2.2	355	9.00	5	0	5	5	5	0	10	0	0	0	0	5	0	10	5	5	0	25
S6N11	0.2-1.2	355	9.00	0	0	0	15	0	0	20	10	10	0	0	0	0	0	15	5	5	5
S6N12	1.2-2.2	355	9.00	5	0	0	10	5	0	35	5	0	0	0	0	0	15	10	5	0	5
S6N13	0.2-1.2	355	9.00	5	0	0	10	5	0	5	10	10	5	0	0	0	0	5	0	10	5
S6N14	1.2-2.2	355	9.00	5	0	5	20	10	0	20	0	0	0	0	5	0	0	15	0	0	10
S6E1	0.2-1.2	90	6.75	0	0	0	10	5	0	10	10	15	10	0	0	0	0	0	10	5	30
S6E2	1.2-2.2	90	6.75	0	0	10	10	0	0	5	0	0	0	0	5	0	5	10	5	0	10
S6E3	0.2-1.2	90	3.38	0	0	10	15	0	0	0	20	10	0	0	0	0	0	0	5	5	10
S6E4	1.2-2.2	90	3.38	0	0	5	10	5	0	5	5	0	0	5	10	0	0	5	15	0	0
S6E5	0.2-1.2	90	6.75	5	0	5	5	5	0	10	25	5	0	0	0	0	0	0	15	5	10
S6E6	1.2-2.2	90	6.75	0	0	10	5	0	0	5	0	0	0	0	5	0	0	5	40	0	10
S6E7	0.2-1.2	90	6.75	5	0	5	5	0	0	15	25	5	0	0	0	0	0	0	30	0	5
S6E8	1.2-2.2	90	6.75	0	0	5	5	0	0	5	0	0	0	0	0	0	5	0	25	0	5
S6S1	0.2-1.2	180	30.38	10	0	5	5	0	0	5	5	5	5	15	0	0	5	5	5	0	15
S6S2	1.2-2.2	180	30.38	10	0	5	5	0	0	5	5	0	0	0	5	0	5	10	15	0	20
S6S3	0.2-1.2	180	30.38	20	0	0	5	0	0	5	0	0	0	0	0	0	0	5	15	5	10
S6S4	1.2-2.2	180	30.38	15	0	5	5	0	0	0	0	0	0	0	0	0	0	10	15	0	5
S6S5	0.2-1.2	180	27.00	10	0	5	10	0	0	5	5	5	5	0	0	0	0	5	5	5	5
S6S6	1.2-2.2	180	27.00	10	0	5	0	0	0	0	0	0	0	0	0	0	0	5	10	0	5
S6S7	0.2-1.2	180	27.00	15	0	5	10	0	0	10	5	5	0	0	0	0	0	5	20	0	5
S6S8	1.2-2.2	180	27.00	20	0	10	0	5	0	0	5	0	0	0	0	0	0	0	25	0	0
S6S9	0.2-1.2	180	27.00	25	0	5	5	0	0	0	5	5	0	0	0	0	0	5	5	0	5
S6S10	1.2-2.2	180	27.00	20	0	5	5	0	0	0	0	0	0	0	5	0	0	10	10	0	5
S6W1	0.2-1.2	270	12.83	5	0	0	15	0	0	10	10	5	0	0	10	0	5	10	5	5	5
S6W2	1.2-2.2	270	12.83	10	0	5	10	0	0	10	0	0	0	0	5	0	15	0	5	0	35
S6W3	0.2-1.2	270	17.10	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S6W4	1.2-2.2	270	17.10	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S6W5	0.2-1.2	270	17.10	10	0	25	10	0	0	5	5	0	5	0	5	0	0	5	5	0	5
S6W6	1.2-2.2	270	17.10	5	0	5	5	0	0	0	5	0	0	0	0	0	0	0	20	0	0
S6W7	0.2-1.2	270	17.10	10	0	0	10	5	0	0	0	10	5	0	5	0	5	0	15	0	0
S6W8	1.2-2.2	270	17.10	0	0	15	5	0	0	0	0	0	0	0	5	0	0	0	20	0	15
S6W9	0.2-1.2	270	17.10	5	0	10	5	0	0	10	0	5	0	0	5	0	0	5	10	0	5
S6W10	1.2-2.2	270	17.10	0	0	5	5	0	0	0	0	0	0	0	5	0	5	10	20	0	25
S7N1	0.2-1.2	2	10.80	5	0	10	15	0	0	5	5	0	5	0	0	0	5	5	0	5	30
S7N2	0.2-1.2	2	10.80	5	0	10	15	0	0	5	5	0	5	0	0	0	0	0	5	0	30
S7N3	0.2-1.2	2	10.80	10	0	10	10	0	0	5	10	5	0	0	0	5	0	5	5	5	0
S7N4	1.2-2.2	2	10.80	10	0	5	10	0	0	0	5	0	0	0	0	0	5	0	15	0	15
S7N5	0.2-1.2	2	10.80	10	0	5	10	0	0	0	15	5	0	0	0	0	0	0	10	5	5

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
S7N6	1.2-2.2	2	10.80	10	0	5	10	0	0	5	0	0	0	10	0	0	0	0	5	0	5
S7N7	0.2-1.2	2	10.80	10	0	5	15	0	20	0	5	5	0	0	5	0	0	5	10	10	5
S7N8	1.2-2.2	2	13.50	15	0	5	5	0	0	0	0	0	0	5	0	0	0	0	5	0	0
S7N9	0.2-1.2	2	5.40	10	0	5	5	0	0	0	0	0	0	0	5	0	10	5	0	0	40
S7N10	1.2-2.2	2	5.40	5	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	40
S7N11	0.2-1.2	2	10.80	5	0	5	0	0	0	0	0	0	5	0	0	0	5	0	0	0	60
S7E1	0.2-1.2	92	9.00	10	0	15	10	0	0	5	5	0	0	0	0	0	5	5	0	0	35
S7E2	1.2-2.2	92	9.00	10	0	20	10	5	0	10	0	0	0	0	0	0	10	5	0	0	10
S7E3	0.2-1.2	92	9.00	10	0	20	10	0	0	5	0	5	0	0	5	0	5	0	10	5	20
S7E4	0.2-1.2	92	9.00	20	0	10	10	0	0	5	5	0	0	0	0	0	0	5	10	0	15
S7E5	1.2-2.2	92	9.00	10	0	10	10	10	0	10	5	0	0	5	0	0	5	5	5	0	5
S7E6	0.2-1.2	92	9.00	5	0	5	10	5	0	10	5	0	0	0	5	0	10	5	5	0	15
S7E7	1.2-2.2	92	9.00	5	0	10	10	5	0	5	0	0	0	10	0	0	5	0	0	0	5
S7E8	0.2-1.2	92	12.00	10	0	0	5	0	0	5	0	0	0	0	0	0	10	0	5	0	50
S7E9	1.2-2.2	92	12.00	15	10	0	10	0	0	5	5	0	0	5	0	0	0	5	15	0	0
S7E10	0.2-1.2	92	12.00	5	0	5	5	0	0	5	0	0	5	0	0	0	5	0	5	0	40
S7E11	1.2-2.2	92	12.00	5	0	10	10	0	0	5	0	0	0	5	0	0	5	0	5	0	5
S7S1	0.2-1.2	180	18.00	25	0	5	0	0	0	0	5	0	0	0	0	0	0	0	20	0	50
S7S2	1.2-2.2	180	24.00	10	0	5	5	0	0	0	5	0	0	0	0	0	5	5	5	0	10
S7S3	0.2-1.2	180	24.00	40	0	0	0	0	0	0	5	0	0	0	0	0	0	0	30	0	30
S7S4	0.2-1.2	180	18.00	10	0	10	5	5	0	10	15	0	0	0	0	0	0	0	15	5	5
S7S5	0.2-1.2	180	18.00	10	0	10	25	5	0	10	5	0	0	5	5	0	5	5	5	0	15
S7S6	0.2-1.2	180	24.00	5	5	0	5	5	0	10	5	0	5	5	0	0	5	5	5	5	15
S7S7	1.2-2.2	180	30.00	15	0	5	10	0	0	10	10	0	0	5	0	0	0	5	0	0	25
S7S8	0.2-1.2	180	24.00	10	0	5	5	0	10	5	0	0	0	0	5	0	10	5	10	0	10
S7S9	0.2-1.2	180	24.00	25	0	10	5	0	0	0	5	0	5	0	5	0	0	5	20	0	15
S7S10	0.2-1.2	180	18.00	5	0	5	5	0	0	0	5	5	0	0	5	0	5	0	10	0	25
S7S11	1.2-2.2	180	18.00	10	0	10	5	0	0	0	5	0	0	0	0	0	0	5	5	0	5
S7W1	0.2-1.2	270	11.25	15	0	30	10	0	0	5	10	0	0	0	5	0	0	0	10	0	5
S7W2	0.2-1.2	270	7.50	10	0	5	10	5	0	5	5	0	0	0	5	0	0	0	15	0	5
S7W3	1.2-2.2	270	7.50	10	0	5	5	0	0	0	5	0	0	0	5	0	5	5	10	0	0
S7W4	0.2-1.2	270	15.00	30	0	5	0	0	0	0	5	0	0	0	5	0	5	0	15	0	15
S7W5	1.2-2.2	270	15.00	5	0	5	5	0	0	0	5	0	0	0	0	0	0	5	20	0	0
S7W6	0.2-1.2	270	15.00	25	0	5	0	0	0	0	5	0	0	0	0	0	0	0	35	0	35
S7W7	1.2-2.2	270	15.00	5	0	0	0	0	0	0	5	0	0	5	0	0	0	0	15	0	5
S7W8	0.2-1.2	270	7.50	15	0	10	5	0	10	0	15	0	0	0	0	0	5	0	10	0	0
S7W9	1.2-2.2	270	7.50	15	0	5	10	0	0	0	5	0	0	0	0	0	0	0	5	0	10
S7W10	0.2-1.2	270	15.00	10	0	40	20	5	0	5	5	0	0	0	0	0	0	5	5	0	0
W1N1	0.2-1.2	334	20.40	5	5	0	0	15	0	0	10	0	5	0	10	15	10	0	15	0	15
W1N2	1.2-2.2	334	20.40	5	0	0	0	15	0	0	10	0	0	0	10	0	15	0	30	0	30
W1N3	0.2-1.2	334	10.20	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	60
W1N4	1.2-2.2	334	10.20	5	0	0	0	45	0	0	5	0	0	0	5	5	5	0	25	0	25
W1N5	0.2-1.2	334	3.40	0	0	0	0	5	0	0	5	0	0	0	5	5	5	0	40	0	20
W1N6	1.2-2.2	334	3.40	0	0	0	0	5	0	0	10	0	0	0	0	0	0	0	70	0	10
W1N7	0.2-1.2	334	13.60	0	0	0	0	5	0	0	0	0	0	0	5	5	0	0	20	0	25
W1N8	1.2-2.2	334	13.60	5	0	0	0	15	0	0	0	0	0	0	15	0	0	0	60	0	10
W1N9	0.2-1.2	334	13.60	0	0	0	0	5	0	0	0	0	0	0	5	0	5	0	20	0	25
W1N10	1.2-2.2	334	13.60	0	0	0	0	15	0	0	0	0	0	0	15	0	0	0	65	0	5
W1N11	0.2-1.2	334	3.40	0	0	0	0	5	0	0	0	0	0	5	0	0	0	5	35	0	25
W1N12	1.2-2.2	334	3.40	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	80	0	5
W1N13	0.2-1.2	334	20.40	5	0	0	0	10	0	0	0	0	0	0	0	0	5	0	35	0	45
W1N14	1.2-2.2	334	20.40	5	0	0	0	10	0	0	0	0	0	0	5	0	5	0	45	0	30
W1N15	0.2-1.2	334	20.40	0	0	0	0	15	0	0	5	0	0	0	0	0	5	10	25	0	40
W1N16	1.2-2.2	334	20.40	5	0	0	0	5	0	0	5	0	0	5	0	0	0	5	45	0	15
W1N17	0.2-1.2	334	15.30	5	0	0	0	10	0	0	0	0	0	0	0	0	10	0	20	0	60
W1N18	1.2-2.2	334	15.30	0	0	0	5	10	0	0	0	0	0	0	5	5	10	0	50	0	15
W1N19	0.2-1.2	334	15.30	5	0	0	5	10	0	0	5	0	0	0	5	0	5	0	30	0	35
W1E1	0.2-1.2	64	3.40	5	0	0	0	10	0	0	0	5	0	0	0	5	0	0	30	0	20
W1E2	1.2-2.2	64	13.60	5	0	0	0	0	0	0	0	0	0	0	5	0	0	0	50	0	0
W1E3	0.2-1.2	64	3.40	5	0	0	0	10	0	0	5	0	5	0	5	0	0	0	30	0	40
W1E4	1.2-2.2	64	10.20	5	0	0	5	5	0	0	0	0	0	0	0	0	0	0	55	0	0
W1E5	0.2-1.2	64	6.80	5	0	0	0	10	0	0	0	0	0	0	0	0	0	0	30	0	20
W1E6	1.2-2.2	64	3.40	5	0	0	0	5	0	0	5	5	0	0	0	5	0	0	75	0	0
W1E7	0.2-1.2	64	3.40	0	0	0	0	0	0	0	5	0	5	0	10	5	5	0	25	0	50
W1E8	1.2-2.2	64	3.40	5	0	0	0	0	0	0	0	0	0	0	5	10	5	0	35	0	30
W1E9	0.2-1.2	64	10.20	0	0	0	0	5	0	0	0	0	0	0	0	5	5	0	20	0	50
W1E10	1.2-2.2	64	3.40	5	0	0	0	5	0	0	0	0	0	0	5	10	5	0	50	0	20
W1E11	0.2-1.2	64	10.20	0	0	0	0	15	0	0	5	0	0	0	0	5	5	0	30	0	30
W1E12	1.2-2.2	64	13.60	0	0	0	0	5	0	0	0	0	0	0	0	5	0	0	20	0	20
W1S1	0.2-1.2	153	34.00	5	0	0	0	0	0	0	20	0	0	10	10	0	0	0	20	0	5
W1S2	1.2-2.2	153	40.80	10	0	0	0	0	0	0	0	0	0	0	0	0	5	0	20	0	10
W1S3	0.2-1.2	153	61.20	10	0	0	0	5	0	0	40	5	0	0	10	0	0	0	20	0	10
W1S4	0.2-1.2	153	40.80	0	0	5	0	5	0	0	15	5	0	0	0	0	0	0	40	0	10
W1S5	0.2-1.2	153	51.00	0	0	0	0	10	0	0	5	15	0	0	0	10	10	0	20	0	20

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
W1S6	0.2-1.2	153	51.00	5	0	0	0	15	0	0	5	0	0	0	5	15	0	0	35	0	15
W1S7	1.2-2.2	153	51.00	5	0	0	0	0	0	0	0	0	0	0	5	0	0	0	80	0	0
W1S8	0.2-1.2	153	51.00	5	0	0	0	0	0	0	5	10	0	0	5	0	0	0	40	0	15
W1S9	1.2-2.2	153	51.00	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	90	0	0
W1S10	0.2-1.2	153	10.20	0	0	0	0	10	0	0	15	5	0	0	10	10	10	0	25	0	15
W1S11	1.2-2.2	153	10.20	5	0	0	0	10	0	0	0	0	0	0	10	5	0	0	50	0	15
W1S12	0.2-1.2	153	30.60	5	0	0	0	15	0	0	5	5	0	0	0	0	0	0	45	0	15
W1S13	1.2-2.2	153	20.40	5	0	0	0	5	0	0	10	0	0	0	5	0	0	0	75	0	0
W1S14	0.2-1.2	153	27.20	5	0	0	0	10	0	0	30	0	0	0	5	5	0	0	40	0	5
W1S15	1.2-2.2	153	27.20	0	0	0	0	20	0	0	0	0	0	0	5	10	0	0	40	0	0
W1S16	0.2-1.2	153	27.20	5	0	0	0	0	0	0	0	0	0	0	5	0	5	0	25	0	35
W1S17	1.2-2.2	153	27.20	5	0	0	0	5	0	0	5	0	0	0	5	0	0	0	80	0	0
W1W1	0.2-1.2	243	20.40	5	0	0	0	20	0	0	10	10	0	0	5	0	0	0	25	0	0
W1W2	1.2-2.2	243	20.40	5	0	0	0	0	0	0	0	0	0	0	5	0	0	0	35	0	0
W1W3	0.2-1.2	243	20.40	10	0	0	0	5	0	0	5	0	0	0	0	0	0	0	35	0	35
W1W4	1.2-2.2	243	30.60	5	0	0	0	0	0	0	5	0	0	0	5	0	0	0	50	0	20
W1W5	0.2-1.2	243	40.80	5	0	0	0	10	0	0	0	0	0	0	5	0	5	0	35	0	35
W1W6	1.2-2.2	243	40.80	5	0	0	0	0	0	0	5	0	0	0	10	10	0	0	60	0	10
W1W7	0.2-1.2	243	27.20	0	0	0	5	10	0	0	10	0	0	0	10	0	5	0	40	0	25
W1W8	1.2-2.2	243	20.40	0	0	0	0	5	0	0	0	0	0	0	5	0	0	5	30	0	15
W1W9	0.2-1.2	243	10.20	0	0	0	0	5	0	0	0	0	0	0	5	0	0	0	70	0	20
W1W10	1.2-2.2	243	10.20	0	0	0	5	0	0	0	0	0	0	0	5	5	0	0	80	0	0
W1W11	0.2-1.2	243	51.00	0	0	5	0	10	0	0	5	5	0	0	10	0	0	0	20	0	10
W1W12	1.2-2.2	243	51.00	5	0	0	0	5	0	0	0	0	0	0	5	5	0	0	35	0	0
W2N1	0.2-1.2	0	4.59	10	0	0	30	20	0	0	10	0	0	0	0	0	0	15	5	0	10
W2N2	1.2-2.2	0	4.59	5	0	0	20	5	0	0	0	0	0	10	0	0	10	10	0	0	40
W2N3	0.2-1.2	0	4.59	5	0	0	20	20	0	0	5	0	5	5	0	0	0	0	10	0	5
W2N4	1.2-2.2	0	4.59	5	0	0	20	10	0	0	0	0	10	10	0	0	0	5	5	0	15
W2N5	0.2-1.2	0	4.59	5	0	0	20	10	0	0	0	0	5	15	0	0	0	0	0	0	10
W2N6	0.2-1.2	0	4.59	5	0	5	5	0	0	0	5	0	0	10	0	0	5	5	5	0	20
W2N7	1.2-2.2	0	4.59	10	0	0	5	10	0	0	0	0	5	10	0	0	0	0	0	0	30
W2N8	0.2-1.2	0	3.06	5	0	0	40	10	0	0	10	0	0	0	0	0	5	10	0	0	15
W2N9	1.2-2.2	0	3.06	10	0	0	10	10	0	0	0	0	0	0	0	0	10	10	0	0	30
W2N10	0.2-1.2	0	3.06	5	0	0	20	15	0	0	0	0	10	10	0	0	0	0	0	0	15
W2N11	1.2-2.2	0	3.06	5	0	0	10	20	0	0	0	0	5	5	0	0	10	10	0	0	15
W2N12	0.2-1.2	0	3.06	5	0	0	10	20	0	0	0	0	0	0	0	0	10	15	0	0	15
W2N13	1.2-2.2	0	3.06	5	0	0	25	0	10	0	0	0	0	0	0	0	15	15	0	0	30
W2N14	0.2-1.2	0	9.18	0	0	0	5	0	0	0	0	0	0	10	0	0	10	10	0	0	10
W2N15	0.2-1.2	0	9.18	5	0	0	30	0	0	0	0	0	0	0	0	0	20	10	0	0	30
W2N16	1.2-2.2	0	9.18	5	0	0	5	5	0	0	0	0	0	0	0	0	15	0	0	0	60
W2E1	0.2-1.2	90	10.20	5	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	5
W2E2	1.2-2.2	90	10.20	5	0	0	0	5	0	0	5	0	0	10	0	0	0	0	0	0	25
W2E3	0.2-1.2	90	6.80	5	0	0	10	5	0	0	0	0	0	0	0	0	0	5	5	0	30
W2E4	1.2-2.2	90	6.80	10	0	0	5	10	0	0	0	0	0	0	0	0	0	0	15	0	30
W2E5	0.2-1.2	90	3.40	0	0	0	5	10	0	0	0	0	0	0	0	0	5	5	0	0	40
W2E6	1.2-2.2	90	3.40	5	0	0	10	10	0	0	0	0	0	0	0	0	5	15	0	0	40
W2E7	0.2-1.2	90	3.40	5	0	0	10	20	0	0	0	0	0	0	0	0	5	5	0	0	50
W2E8	1.2-2.2	90	3.40	5	0	0	15	10	0	0	0	0	0	0	0	0	15	5	0	0	40
W2E9	0.2-1.2	90	3.40	10	0	0	15	30	0	0	0	0	0	0	0	0	20	0	0	0	20
W2E10	1.2-2.2	90	3.40	5	0	0	10	10	0	0	0	0	0	0	0	0	25	5	0	0	45
W2E11	0.2-1.2	90	10.20	5	0	0	15	25	0	0	0	0	20	10	0	0	0	0	0	0	25
W2E12	1.2-2.2	90	10.20	0	0	0	15	25	0	0	0	0	25	5	0	0	0	0	0	0	25
W2S1	0.2-1.2	180	30.60	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
W2S2	1.2-2.2	180	30.60	5	0	0	0	5	0	0	0	0	0	0	0	0	0	5	10	0	0
W2S3	0.2-1.2	180	20.40	5	0	0	5	0	0	0	0	0	0	5	0	0	0	5	5	0	5
W2S4	1.2-2.2	180	20.40	10	0	0	5	0	0	0	0	0	0	0	0	0	0	0	10	0	0
W2S5	0.2-1.2	180	20.40	5	0	0	40	5	0	0	0	0	0	0	0	0	0	5	5	0	10
W2S6	1.2-2.2	180	20.40	5	0	0	10	10	0	0	5	0	0	5	0	0	0	0	10	0	5
W2S7	0.2-1.2	180	30.60	5	0	0	0	0	0	0	0	0	0	0	0	0	0	10	5	0	5
W2S8	1.2-2.2	180	30.60	5	0	0	0	5	0	0	5	0	0	5	0	0	0	0	10	0	5
W2S9	0.2-1.2	180	10.20	15	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5	0	10
W2S10	1.2-2.2	180	10.20	5	0	0	0	5	0	0	0	0	0	5	0	0	0	0	0	0	0
W2S11	0.2-1.2	180	20.40	5	0	0	5	5	0	0	0	0	0	0	0	0	0	5	5	0	10
W2S12	1.2-2.2	180	20.40	10	0	0	10	0	0	0	5	0	0	0	0	0	0	5	20	0	20
W2S13	0.2-1.2	180	40.80	0	0	0	15	30	0	0	0	0	0	0	0	0	20	10	0	0	20
W2S14	1.2-2.2	180	40.80	5	0	0	0	10	0	0	0	0	0	0	0	0	0	0	5	0	15
W2S15	0.2-1.2	180	40.80	15	0	0	10	10	0	0	0	0	0	0	0	0	10	50	0	0	5
W2S16	1.2-2.2	180	40.80	10	0	0	5	10	0	0	5	0	0	0	0	0	5	10	5	0	10
W2S17	0.2-1.2	180	51.00	15	0	0	10	5	0	0	0	0	0	0	0	0	0	10	0	0	10
W2S18	1.2-2.2	180	51.00	20	0	0	5	5	0	0	0	0	0	0	0	0	0	5	0	0	20
W2W1	0.2-1.2	270	17.00	10	0	0	10	20	0	0	0	0	0	0	0	0	10	10	0	0	5
W2W2	1.2-2.2	270	17.00	5	0	0	5	5	0	0	0	0	0	0	0	0	0	5	5	0	0
W2W3	0.2-1.2	270	12.75	5	0	0	40	0	0	0	0	0	0	5	0	0	0	10	0	0	5
W2W4	1.2-2.2	270	12.75	5	0	0	25	10	0	0	0	0	0	10	0	0	0	10	0	0	5

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
W2W5	0.2-1.2	270	12.75	0	0	0	5	20	0	0	0	0	0	0	0	0	0	5	0	0	10
W2W6	0.2-1.2	270	12.75	5	0	0	10	5	0	0	0	0	0	0	0	0	5	5	0	0	50
W2W7	1.2-2.2	270	12.75	0	0	0	10	20	0	0	0	0	0	0	0	0	10	10	0	0	40
W3N1,1	0.2-1.2	342	22.95	5	0	5	10	5	0	10	0	0	5	10	0	0	5	5	0	0	15
W3N1,2	1.2-2.2	342	22.95	5	0	0	10	5	5	5	0	5	0	5	0	5	0	5	5	0	5
W3N1,3	0.2-1.2	342	27.54	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3N1,4	1.2-2.2	342	27.54	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3N1,5	0.2-1.2	342	22.95	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3N1,6	1.2-2.2	342	22.95	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3N1,7	0.2-1.2	342	18.36	5	0	25	5	0	0	10	0	0	5	0	0	0	10	0	0	0	25
W3N1,8	1.2-2.2	342	18.36	5	0	15	15	0	0	10	0	5	0	5	0	0	20	10	0	0	15
W3N1,9	0.2-1.2	342	18.36	0	0	30	0	0	0	5	0	5	0	0	0	0	10	5	0	0	20
W3N2,1	0.2-1.2	342	18.36	10	0	5	10	5	0	5	0	5	10	0	0	0	10	0	0	0	20
W3N2,2	1.2-2.2	342	18.36	10	0	5	5	0	0	5	0	0	5	0	0	0	5	0	0	0	40
W3N2,3	0.2-1.2	342	9.18	5	0	15	5	0	0	5	0	0	5	5	0	0	10	0	0	0	30
W3N2,4	0.2-1.2	342	9.18	5	0	10	5	0	0	5	0	0	5	5	0	0	5	0	0	0	30
W3N2,5	1.2-2.2	342	13.77	5	0	5	0	10	0	5	0	0	0	0	0	0	10	0	0	0	40
W3N2,6	0.2-1.2	342	13.77	5	0	5	5	10	20	5	0	5	10	0	0	0	5	0	0	0	20
W3N2,7	0.2-1.2	342	22.95	5	0	5	0	0	0	5	0	0	5	0	0	0	10	0	0	0	40
W3N2,8	1.2-2.2	342	22.95	5	0	5	0	0	0	5	0	0	5	0	0	0	0	0	0	0	40
W3N2,9	0.2-1.2	342	27.54	5	0	5	5	0	0	10	0	0	0	5	0	0	5	5	0	0	40
W3N2,10	1.2-2.2	342	27.54	10	0	5	0	0	0	5	0	0	5	0	0	0	0	5	0	0	15
W3E1	0.2-1.2	73	30.60	0	0	0	5	0	0	5	5	0	0	20	0	0	0	5	0	0	10
W3E2	1.2-2.2	73	30.60	0	0	5	5	5	0	5	0	0	0	25	0	0	0	0	0	0	10
W3E3	0.2-1.2	73	30.60	5	0	5	0	0	0	0	0	0	10	5	0	0	0	5	0	0	30
W3E4	1.2-2.2	73	30.60	10	0	5	10	0	10	5	0	0	0	5	0	0	0	10	10	0	10
W3E5	0.2-1.2	73	30.60	5	0	0	0	0	5	10	0	0	5	0	0	0	15	15	0	0	30
EW36	0.2-1.2	73	45.90	5	0	0	5	0	0	5	0	0	10	5	0	0	5	5	0	0	40
W3E7	1.2-2.2	73	45.90	10	0	5	0	0	0	15	0	0	0	0	0	0	5	5	0	0	10
W3E8.	0.2-1.2	73	30.60	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3E9	1.2-2.2	73	30.60	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3S1	0.2-1.2	163	45.26	5	0	15	5	0	0	5	0	0	5	0	0	0	0	0	0	0	25
W3S2	1.2-2.2	163	45.26	5	0	10	5	0	0	5	0	0	0	0	0	0	5	0	0	0	10
W3S3	0.2-1.2	163	45.26	5	0	5	5	0	5	5	5	0	0	10	0	0	0	5	5	0	0
W3S4	0.2-1.2	163	45.26	5	0	5	5	0	0	10	0	0	0	10	0	0	0	5	0	0	5
W3S5	1.2-2.2	163	45.26	5	0	5	0	0	0	5	0	0	0	0	0	0	5	5	0	0	20
W3S6	0.2-1.2	163	45.26	5	0	5	5	0	0	15	5	0	0	5	0	0	5	10	5	0	5
W3S7	1.2-2.2	163	45.26	5	0	5	5	0	0	5	5	0	0	5	0	0	0	5	0	0	10
W3S8	0.2-1.2	163	45.26	5	0	10	0	0	0	15	10	0	0	5	0	0	0	5	5	0	5
W3S9	1.2-2.2	163	45.26	5	0	0	0	0	0	5	0	5	0	0	0	0	0	0	0	0	10
W3S10	0.2-1.2	163	45.26	20	0	10	10	0	0	5	5	0	5	0	0	0	0	5	5	0	15
W3S11	0.2-1.2	163	36.21	5	0	5	5	5	0	15	5	0	5	5	0	0	5	5	0	0	25
W3S12	1.2-2.2	163	36.21	35	0	0	0	0	0	5	5	0	0	0	5	0	0	5	5	0	0
W3W1	0.2-1.2	256	25.50	0	0	40	5	0	0	5	5	5	0	5	0	0	5	5	0	0	0
W3W2	1.2-2.2	256	25.50	5	0	15	0	0	0	5	0	0	0	0	0	0	0	5	5	0	0
W3W3	0.2-1.2	256	4.25	5	0	25	10	5	0	5	0	0	0	0	0	0	15	10	0	0	10
W3W4	1.2-2.2	256	12.75	5	0	10	5	5	0	5	0	0	0	5	0	0	10	5	0	0	15
W3W5	0.2-1.2	256	4.25	5	0	60	5	0	0	10	0	0	0	0	0	0	10	0	0	0	10
W3W6	0.2-1.2	256	4.25	5	0	50	0	0	0	5	0	0	0	0	0	0	5	0	0	0	20
W3W7	1.2-2.2	256	12.75	5	0	15	5	0	0	5	0	0	0	0	0	0	5	5	0	0	30
W3W8	0.2-1.2	256	17.00	0	0	0	5	0	0	15	5	5	0	40	0	0	0	10	5	0	5
W3W9	1.2-2.2	256	17.00	0	0	0	5	0	0	10	0	5	0	15	0	0	0	0	5	0	5
W4N1	0.2-1.2	335	10.80	5	0	0	5	5	0	5	0	0	0	0	0	5	5	5	5	5	10
W4N2	1.2-2.2	335	10.80	5	0	0	0	0	0	5	0	0	0	0	5	0	10	10	5	0	30
W4N3	0.2-1.2	335	16.20	5	0	5	5	0	0	10	0	0	0	0	0	0	10	0	5	0	60
W4N4	1.2-2.2	335	16.20	5	0	0	5	5	0	5	0	0	0	0	0	0	5	0	10	0	5
W4E1	0.2-1.2	65	8.10	10	0	0	10	5	0	10	0	5	0	5	0	0	0	5	5	0	10
W4E2	0.2-1.2	65	12.15	5	0	0	5	0	0	5	0	0	0	5	0	0	5	0	10	0	30
W4E3	1.2-2.2	65	12.15	5	0	0	0	0	0	5	0	0	0	0	0	0	5	0	10	0	40
W4E4	0.2-1.2	65	12.15	5	0	0	5	5	0	10	0	0	0	0	0	0	5	5	5	0	20
W4E5	0.2-1.2	65	12.15	5	0	0	0	0	0	10	0	0	0	0	5	0	5	0	5	0	25
W4E6	1.2-2.2	65	12.15	5	0	0	5	5	0	0	0	0	0	0	0	0	5	5	5	0	40
W4E7	0.2-1.2	65	12.15	5	0	0	5	0	0	5	0	0	0	0	0	0	5	5	10	0	20
W4E8	0.2-1.2	65	12.15	5	0	0	5	0	0	10	5	0	0	0	0	0	5	5	5	0	25
W4E9	1.2-2.2	65	12.15	5	0	0	0	0	0	5	0	0	5	0	0	0	5	0	10	0	30
W4E10	0.2-1.2	65	12.15	5	0	0	5	0	0	10	5	0	0	0	5	0	5	5	5	0	35
W4E11	1.2-2.2	65	12.15	10	0	0	0	0	0	5	0	0	0	0	0	0	5	5	5	0	35
W4E12	0.2-1.2	65	12.15	0	0	0	0	0	0	5	0	0	0	5	0	0	5	5	5	0	10
W4S1	0.2-1.2	155	26.63	5	0	0	0	0	0	5	5	0	0	0	0	0	5	5	5	0	25
W4S2	1.2-2.2	155	26.63	5	0	0	0	0	0	5	0	0	0	0	5	0	5	5	10	0	25
W4S3	0.2-1.2	155	5.33	5	0	0	5	5	0	5	0	0	0	0	0	0	10	0	10	0	40
W4S4	1.2-2.2	155	5.33	5	0	0	0	0	0	5	0	0	0	0	0	0	15	5	0	0	35
W4W1	0.2-1.2	245	15.98	5	0	0	5	10	0	5	0	0	0	0	5	0	0	10	10	0	0
W4W2	0.2-1.2	245	15.98	10	0	5	5	0	0	5	5	0	0	0	5	0	0	5	15	0	10

Obs. Code	Height (m)	Orien. E of N	*DWA*	Rel.	Alv.	Anthr.	Gran. dis.	Mul. fla.	Mul. sca.	Spal.	Bla. fla.	Cas. fla.	Aut. fla.	Una. fla.	Bla. sca.	Cas. sca.	Aut. sca.	Una. Sca.	Bla. soi.	Cas. soi.	Aut. soi.
W4W3	1.2-2.2	245	15.98	5	0	0	0	0	0	0	0	0	0	0	5	0	5	5	15	0	15
W4W4	0.2-1.2	245	15.98	5	0	0	5	5	0	10	5	5	0	0	5	0	0	5	20	0	0
W4W5	0.2-1.2	245	15.98	10	0	0	5	0	0	5	5	0	0	0	0	0	0	5	15	0	5
W4W6	1.2-2.2	245	15.98	10	0	0	5	5	0	5	0	0	0	0	5	0	0	5	15	0	10
W4W7	0.2-1.2	245	15.98	5	0	0	5	0	0	5	5	0	0	0	5	0	0	5	10	0	0
W4W8	0.2-1.2	245	15.98	5	0	0	5	0	0	5	10	0	0	0	5	0	0	5	15	0	5
W4W9	1.2-2.2	245	15.98	10	0	0	0	0	0	5	0	0	0	0	5	0	0	5	20	0	5
W4W10	0.2-1.2	245	15.98	5	0	0	5	10	0	5	5	0	0	0	5	0	0	10	10	0	5
W4W11	0.2-1.2	245	23.96	5	0	0	5	5	0	10	10	0	0	0	5	0	0	10	10	0	0
W4W12	1.2-2.2	245	23.96	5	0	0	5	0	0	5	0	0	0	0	5	0	0	5	25	0	0
W5N1	0.2-1.2	2	8.10	0	0	5	10	5	0	10	5	10	10	0	5	0	10	5	5	5	5
W5N2	1.2-2.2	2	8.10	10	0	5	10	0	10	10	5	0	0	0	0	0	15	0	5	0	10
W5N3	0.2-1.2	2	10.80	5	0	5	10	0	0	10	0	10	5	0	0	0	5	0	0	5	20
W5N4	0.2-1.2	2	10.80	5	0	5	15	0	0	5	0	10	5	5	0	0	10	0	0	5	10
W5N5	1.2-2.2	2	10.80	5	0	0	5	5	0	10	0	0	5	5	0	0	15	0	0	0	25
W5N6	0.2-1.2	2	10.80	10	0	5	10	0	0	15	5	5	5	0	0	0	5	0	5	5	5
W5N7	0.2-1.2	2	5.40	10	0	20	15	5	0	5	0	5	5	0	0	0	5	0	0	5	20
W5N8	1.2-2.2	2	10.80	10	0	10	10	0	0	5	0	0	5	5	0	0	10	5	0	0	25
W5N9	0.2-1.2	2	10.80	15	0	0	10	0	0	0	0	5	5	0	0	0	0	0	5	0	40
W5N10	1.2-2.2	2	10.80	5	0	5	5	0	0	10	0	0	5	0	0	0	15	0	0	0	40
W5N11	0.2-1.2	2	13.50	5	0	5	20	0	0	10	0	0	5	0	0	0	20	0	0	5	20
W5N12	0.2-1.2	2	10.80	20	0	40	5	0	0	5	0	0	0	0	0	0	5	0	0	0	15
W5N13	1.2-2.2	2	13.50	15	0	5	5	0	0	5	0	0	0	0	0	0	10	0	0	0	30
W5E1	0.2-1.2	90	12.00	10	0	5	5	0	5	20	5	0	0	0	0	0	10	0	5	5	15
W5E2	1.2-2.2	90	12.00	10	0	5	5	0	5	10	0	0	0	0	0	0	10	5	5	0	10
W5E3	0.2-1.2	90	9.00	10	0	5	10	5	0	5	10	0	0	0	5	0	0	10	10	0	10
W5E4	1.2-2.2	90	12.00	10	0	5	5	5	0	5	10	0	0	5	5	0	0	0	25	0	0
W5E5	0.2-1.2	90	12.00	10	0	10	10	10	0	10	5	5	0	0	5	0	0	0	10	5	15
W5E6	1.2-2.2	90	12.00	10	0	10	10	0	0	5	10	5	0	0	0	0	0	0	25	5	5
W5E7	0.2-1.2	90	12.00	10	0	15	10	5	0	15	10	5	5	0	0	0	0	0	20	0	5
W5E8	1.2-2.2	90	12.00	10	0	5	5	0	0	10	15	10	0	0	0	0	0	0	30	5	0
W5E9	0.2-1.2	90	6.00	5	0	5	10	5	0	5	25	5	0	0	0	0	5	0	35	0	0
W5E10	1.2-2.2	90	6.00	10	0	0	10	0	0	5	0	5	15	0	0	0	10	0	0	0	50
W5S1	0.2-1.2	182	24.00	10	0	5	10	0	10	5	10	5	0	5	0	0	0	5	5	5	0
W5S2	1.2-2.2	182	24.00	20	0	5	5	0	0	5	5	5	5	0	0	0	5	5	0	0	15
W5S3	0.2-1.2	182	18.00	20	0	5	10	5	0	0	0	0	0	0	0	0	5	10	5	0	5
W5S4	1.2-2.2	182	18.00	15	0	5	5	0	0	0	0	0	0	0	0	0	5	5	0	0	15
W5S5	0.2-1.2	182	18.00	5	0	15	10	0	0	5	10	10	0	0	5	0	10	0	5	5	5
W5S6	1.2-2.2	182	18.00	5	0	5	5	0	0	5	15	0	0	0	0	0	0	0	40	0	0
W5S7	0.2-1.2	182	24.00	25	0	0	5	0	0	0	0	0	5	0	0	0	0	0	0	0	60
W5S8	1.2-2.2	182	24.00	25	0	5	10	0	5	10	0	5	5	0	0	0	5	0	0	5	10
W5S9	0.2-1.2	182	36.00	10	0	5	5	0	0	10	15	5	0	5	0	0	0	5	5	0	5
W5S10	1.2-2.2	182	36.00	20	0	5	10	0	0	10	10	0	5	0	0	0	0	5	5	0	5
W5S11	0.2-1.2	182	24.00	20	0	10	5	0	0	0	10	0	0	0	0	0	0	0	10	0	0
W5S12	1.2-2.2	182	24.00	15	0	0	5	5	0	5	5	0	0	0	0	0	5	5	5	0	5
W5W1	0.2-1.2	272	8.50	15	0	5	5	0	0	5	10	10	0	0	0	0	5	10	5	5	5
W5W2	1.2-2.2	272	8.50	25	0	10	5	0	0	5	0	0	0	0	0	0	5	5	0	0	25
W5W3	0.2-1.2	272	12.75	15	0	5	10	0	0	5	10	0	0	0	0	0	5	5	5	5	5
W5W4	1.2-2.2	272	12.75	10	0	0	5	0	0	5	0	0	5	0	0	0	5	10	0	0	30

APPENDIX 4
MONTHLY MEANS AND STANDARD DEVIATIONS FOR VARIABLES RECORDED AT LICHFIELD CATHEDRAL

Month	Statistic	Aspect			
		N	E	S	W
1.94	Mean	6.1	6.5	7.3	6.6
	SD	2.3	2.2	3.1	2.7
2.94	Mean	2.7	2.8	3.3	3.3
	SD	3.2	3.2	3.9	3.6
3.94	Mean	7.3	8.2	8.5	7.8
	SD	3.0	3.2	4.0	3.6
4.94	Mean	8.0	9.4	9.5	8.8
	SD	4.7	5.1	5.5	5.4
5.94	Mean	12.0	13.5	13.2	12.8
	SD	3.5	4.4	4.5	5.0
6.94	Mean	14.9	16.2	15.7	15.4
	SD	4.1	4.2	4.5	5.2
7.94	Mean	N/D	N/D	N/D	N/D
	SD	N/D	N/D	N/D	N/D
8.94	Mean	15.3	16.8	17.2	16.4
	SD	3.1	3.8	4.5	4.9
9.94	Mean	12.1	13.1	13.5	13.0
	SD	2.5	3.2	3.6	3.7
1.94	Mean	9.3	9.8	10.7	10.7
	SD	2.9	2.9	3.9	4.7
11.94	Mean	9.6	9.9	10.2	10.3
	SD	2.5	2.4	2.8	2.9
12.94	Mean	5.6	5.7	6.4	6.4
	SD	4.1	4.0	4.0	4.2
1.95	Mean	3.9	4.2	4.6	4.6
	SD	3.1	3.1	3.4	3.3
2.95	Mean	5.8	6.4	6.9	6.5
	SD	2.7	2.8	3.5	3.2
3.95	Mean	4.9	6.4	7.3	6.2
	SD	3.5	3.9	5.1	4.9
4.95	Mean	9.2	10.3	11.2	10.8
	SD	3.8	4.3	5.3	5.6
5.95	Mean	12.6	14.2	14.4	13.4
	SD	5.2	6.0	6.5	6.4
6.95	Mean	15.0	16.0	16.5	16.2
	SD	4.9	5.2	5.9	6.7
7.95	Mean	20.1	21.3	21.1	20.9
	SD	5.0	5.3	5.7	6.5
Annual mean*	Mean	14.5	15.9	16.5	15.8
	SD	5.3	5.8	6.6	6.9

Table A4.1 Means and standard deviations of monthly sandstone temperatures (^{o}C) at Lichfield Cathedral (*if two sets of data exist for the same month the mean of those two months is used to calculate the annual mean).

Date	Statistic	Aspect			
		N	E	S	W
1.94	Mean	0.10	0.09	0.24	0.21
	SD	0.14	0.14	0.41	0.34
2.94	Mean	0.10	0.11	0.17	0.19
	SD	0.12	0.18	0.29	0.36
3.94	Mean	0.14	0.18	0.26	0.26
	SD	0.17	0.29	0.40	0.40
4.94	Mean	0.19	0.25	0.32	0.35
	SD	0.21	0.37	0.43	0.49
5.94	Mean	0.24	0.31	0.34	0.40
	SD	0.23	0.44	0.46	0.51
6.94	Mean	0.28	0.32	0.32	0.38
	SD	0.30	0.47	0.45	0.51
7.94	Mean	N/D	N/D	N/D	N/D
	SD	N/D	N/D	N/D	N/D
8.94	Mean	0.21	0.28	0.37	0.41
	SD	0.23	0.45	0.53	0.63
9.94	Mean	0.15	0.20	0.28	0.34
	SD	0.19	0.38	0.46	0.60
1.94	Mean	0.13	0.15	0.26	0.36
	SD	0.16	0.25	0.42	0.65
11.94	Mean	0.08	0.08	0.14	0.17
	SD	0.12	0.15	0.28	0.35
12.94	Mean	0.10	0.09	0.19	0.21
	SD	0.13	0.13	0.34	0.39
1.95	Mean	0.10	0.10	0.18	0.19
	SD	0.16	0.16	0.32	0.38
2.95	Mean	0.11	0.15	0.23	0.24
	SD	0.17	0.26	0.39	0.45
3.95	Mean	0.16	0.24	0.36	0.38
	SD	0.19	0.41	0.53	0.62
4.95	Mean	0.20	0.25	0.36	0.43
	SD	0.22	0.39	0.50	0.65
5.95	Mean	0.27	0.34	0.39	0.44
	SD	0.27	0.48	0.52	0.59
6.95	Mean	0.27	0.27	0.31	0.41
	SD	0.30	0.39	0.41	0.52
7.95	Mean	0.32	0.33	0.37	0.48
	SD	0.32	0.46	0.47	0.58
Annual mean	Mean	0.26	0.31	0.42	0.49
	SD	0.30	0.48	0.63	0.75

Table A4.2 Means and standard deviations of monthly sandstone temperature changes per fifteen minutes (^{o}C) at Lichfield Cathedral (*if two sets of data exist for the same month the mean of those two months is used to calculate the annual mean).

Month	Statistic	Aspect			
		N	E	S	W
6.94	Mean	70.7	83.2	65.1	74.3
	SD	6.1	3.8	6.4	10.0
7.94	Mean	N/D	N/D	N/D	N/D
	SD	N/D	N/D	N/D	N/D
8.94	Mean	80.6	65.4	N/D	73.1
	SD	10.4	3.6	N/D	10.9
9.94	Mean	93.4	90.3	75.2	91.4
	SD	6.1	9.3	9.4	6.3
10.94	Mean	96.0	94.0	78.0	90.0
	SD	2.1	1.5	8.1	8.6
11.94	Mean	98.9	96.1	96.8	97.2
	SD	1.3	1.7	4.2	1.3
12.94	Mean	98.2	95.7	96.6	98.4
	SD	1.2	0.9	4.5	1.8
1.95	Mean	99.4	95.5	94.5	99.5
	SD	0.6	1.2	6.4	1.5
2.95	Mean	99.3	96.9	98.1	98.8
	SD	0.7	0.9	2.5	2.0
3.95	Mean	98.5	97.1	91.7	94.5
	SD	1.7	1.2	10.3	6.6
4.95	Mean	90.9	N/D	74.4	78.4
	SD	4.9	N/D	12.2	8.4
5.95	Mean	77.1	N/D	49.7	71.1
	SD	10.1	N/D	14.2	11.6
6.95	Mean	71.7	N/D	50.0	71.0
	SD	10.4	N/D	12.7	14.2
7.95	Mean	61.3	N/D	43.7	64.1
	SD	8.1	N/D	10.2	12.6
Mean	Mean	94.3	N/D	87.0	93.0
	SD	2.5	N/D	6.5	4.8

Table A4.3 Means and standard deviations of monthly sandstone relative humidity (%) at Lichfield Cathedral (*the mean is calculated only from monthly values where data was available for all aspects, i.e. 6.94, 9.94, 10.94, 11.94, 12.94, 1.95, 2.95 and 3.95).

Month	Statistic	Aspect			
		N	E	S	W
6.94	Mean	0.26	0.27	0.34	0.36
	SD	0.46	0.52	0.52	0.63
7.94	Mean	N/D	N/D	N/D	N/D
	SD	N/D	N/D	N/D	N/D
8.94	Mean	0.23	0.24	N/D	0.38
	SD	0.48	0.52	N/D	0.61
9.94	Mean	0.20	0.14	0.18	0.23
	SD	0.43	0.36	0.41	0.50
10.94	Mean	0.16	0.18	0.19	0.27
	SD	0.40	0.41	0.42	0.56
11.94	Mean	0.08	0.10	0.06	0.13
	SD	0.27	0.32	0.24	0.37
12.94	Mean	0.13	0.13	0.07	0.13
	SD	0.34	0.34	0.34	0.36
1.95	Mean	0.11	0.14	0.10	0.10
	SD	0.31	0.35	0.43	0.40
2.95	Mean	0.12	0.12	0.05	0.19
	SD	0.33	0.33	0.21	0.54
3.95	Mean	0.15	0.17	0.12	0.40
	SD	0.38	0.39	0.35	0.89
4.95	Mean	0.19	0.22	0.33	0.47
	SD	0.45	0.46	0.67	0.83
5.95	Mean	0.26	0.29	0.34	0.43
	SD	0.49	0.54	0.61	0.69
6.95	Mean	0.29	0.27	0.31	0.43
	SD	0.51	0.53	0.54	0.69
7.95	Mean	0.31	0.27	0.33	0.56
	SD	0.50	0.53	0.54	0.77
Mean*	Mean	0.15	0.16	0.14	0.23
	SD	0.37	0.38	0.37	0.53

Table A4.4 Means and standard deviations of monthly sandstone relative humidity (%) changes per fifteen minutes at Lichfield Cathedral (*the mean is calculated only from monthly values where data was available for all aspects, i.e. 6.94, 9.94, 10.94, 11.94, 12.94, 1.95, 2.95 and 3.95).

Month	Statistic	Aspect			
		N	E	S	W
6.94	Mean	0.26	0.27	0.34	0.36
	SD	0.46	0.52	0.52	0.63
7.94	Mean	N/D	N/D	N/D	N/D
	SD	N/D	N/D	N/D	N/D
8.94	Mean	0.23	0.24	N/D	0.38
	SD	0.48	0.52	N/D	0.61
9.94	Mean	0.20	0.14	0.18	0.23
	SD	0.43	0.36	0.41	0.50
10.94	Mean	0.16	0.18	0.19	0.27
	SD	0.40	0.41	0.42	0.56
11.94	Mean	0.08	0.10	0.06	0.13
	SD	0.27	0.32	0.24	0.37
12.94	Mean	0.13	0.13	0.07	0.13
	SD	0.34	0.34	0.34	0.36
1.95	Mean	0.11	0.14	0.10	0.10
	SD	0.31	0.35	0.43	0.40
2.95	Mean	0.12	0.12	0.05	0.19
	SD	0.33	0.33	0.21	0.54
3.95	Mean	0.15	0.17	0.12	0.40
	SD	0.38	0.39	0.35	0.89
4.95	Mean	0.19	0.22	0.33	0.47
	SD	0.45	0.46	0.67	0.83
5.95	Mean	0.26	0.29	0.34	0.43
	SD	0.49	0.54	0.61	0.69
6.95	Mean	0.29	0.27	0.31	0.43
	SD	0.51	0.53	0.54	0.69
7.95	Mean	0.31	0.27	0.33	0.56
	SD	0.50	0.53	0.54	0.77
Mean*	Mean	0.15	0.16	0.14	0.23
	SD	0.37	0.38	0.37	0.53

Table A4.4 Means and standard deviations of monthly sandstone relative humidity (%) changes per fifteen minutes at Lichfield Cathedral (*the mean is calculated only from monthly values where data was available for all aspects, i.e. 6.94, 9.94, 10.94, 11.94, 12.94, 1.95, 2.95 and 3.95).

APPENDIX 5
GEOCHEMISTRY REFERENCE MATERIALS USED FOR XRF CALIBRATION

Material	International reference code	Issuing body
Albite	AL-1	Groupe Internationale de Travail
Andesite	AGV-1	United States Geological Survey
Andesite	JA-2	Geological Survey of Japan
Andesite	JA-3	Geological Survey of Japan
Basalt	BE-N	Groupe Internationale de Travail
Basalt	JB-2	Geological Survey of Japan
Basalt	JB-3	Geological Survey of Japan
Shale	SCo-1	United States Geological Survey
Diabase	W-2	United States Geological Survey
Diorite	DR-1	Association Nationale de la Researche Technique
Kyanite	DT-N	Association Nationale de la Researche Technique
Diabase	DNC-1	United States Geological Survey
Potash Feldspar	FK-1	Association Nationale de la Researche Technique
Feldspar	JF-1	Geological Survey of Japan
Feldspar	JF-2	Geological Survey of Japan
Gabbro	JGb-1	Geological Survey of Japan
Granite	G-2	United States Geological Survey
Granite	GS-N	Association Nationale de la Researche Technique
Granite	JG-2	Geological Survey of Japan
Granodiorite	JG-1a	Geological Survey of Japan
Granodiorite	JG-3	Geological Survey of Japan
Shale	SGR-1	United States Geological Survey
Basalt	BIR-1	United States Geological Survey
Lugaurite	SARM-3	United States Geological Survey
Marine mud	MAG-1	United States Geological Survey
Clay soil	SO-1	Canadian Certified Reference Material Project
Podzolic soil	SO-2	Canadian Certified Reference Material Project
Calcareous soil	SO-3	Canadian Certified Reference Material Project
Chernozemic soil	SO-4	Canadian Certified Reference Material Project
Mica Schist	SDC-1	United States Geological Survey
Mn nodules	NOD-A-1	United States Geological Survey
Mn nodules	NOD-P-1	United States Geological Survey
Syenite	STM-1	United States Geological Survey
Peridotite	JP-1	Geological Survey of Japan
Quartz Latite	QLO-1	United States Geological Survey
Rhyolite	JR-1	Geological Survey of Japan
Rhyolite	JR-2	Geological Survey of Japan
Rhyolite	RGM-1	United States Geological Survey
Serpentine	UB-N	Association Nationale de la Researche Technique
Shale	SDo-1	United States Geological Survey

Table A5.1 International reference materials with unique codes, allowing further information to be obtained from good geochemistry reference books, such as Potts (1987).

APPENDIX 6

CALCULATING RATES OF KAOLINITE FORMATION AND THE SUBSEQUENT REDUCTION IN SANDSTONE STRENGTH

Based on the following assumptions the weakening of the sandstone can be estimated using Equation A6.1, Equation A6.2 and the relevant atomic weights (Table A6.1):

1. Potassium loss is a good indicator of the rate of kaolinite ($Al_4Si_4O_{10}(OH)_8$) formation.
2. Kaolinite formation is linear over time.
3. The estimate of a reduction in compressive strength of 10 N mm^{-2} for every one per cent increase in kaolinite is valid (Sramek, 1992).

It can be calculated that the loss of 487.6 mg m^{-2} of potassium will create 1609.6 mg m^{-2} yr^{-1} of kaolinite (Equation A6.2). The sandstone microcatchments weigh approximately 98858 g m^{-2}, so the kaolinite formed in one year is 0.00163% of the weight of a metre squared microcatchment. Therefore, it will take approximately 60 years to produce 0.1% kaolinite which according to Sramek (1992) will cause a 1 N mm^{-2} decrease in strength.

$$4KAlSi_3O_8 + 8H^+ \rightarrow Al_4Si_4O_{10}(OH)_8 + 4K^+ + 8Si^+ + 14O^{2-}$$

Equation A6.1

$$\mathbf{WK = (AK / AP) * WP}$$

where

WK = weight of $Al_4Si_4O_{10}(OH)_8$

AK = atomic weight of $Al_4Si_4O_{10}(OH)_8$ = 516.3

AP = atomic weight of $4K^+$ = 156.4

WP = weight of potassium lost = 487.6 mg m^{-2} yr^{-1}

Equation A6.2

Element	Atomic weight
K	39.098
Al	26.982
Si	28.086
O	15.999
H	1.008

Table A6.1 Atomic weights of relevant elements.

APPENDIX 7
DATA FROM THE
MICROCATCHMENT EXPERIMENT

Week	Date	Part. mat.	Al	As	Ca	Fe	K	Mg	Na	Pb	Si	Sr	Zn	Sulphate	Chloride	Nitrate
1	5.10.93	-120.16	-0.13	-1.66	-20.85	0.00	-15.78	2.88	-14.53	-0.03	-10.12	-0.14	0.49	-21.64	-23.75	8.96
2	12.10.93	-265.19	-0.14	-1.93	-84.16	0.00	-50.43	3.06	-43.35	-0.03	-36.14	-0.15	1.70	-123.02	-60.88	3.77
3	19.10.93	-290.59	0.11	-3.24	-122.86	0.00	-70.91	3.27	-52.16	0.28	-42.05	-0.17	2.00	-187.73	-59.83	-6.87
4	26.10.93	-290.59	0.11	-3.24	-122.86	0.00	-70.91	3.27	-52.16	0.28	-42.05	-0.17	2.00	-187.73	-59.83	-6.87
5	2.11.93	-290.59	0.11	-3.24	-122.86	0.00	-70.91	3.27	-52.16	0.28	-42.05	-0.17	2.00	-187.73	-59.83	-6.87
6	9.11.93	-290.59	0.11	-3.24	-122.86	0.00	-70.91	3.27	-52.16	0.28	-42.05	-0.17	2.00	-187.73	-59.83	-6.87
7	16.11.93	-1152.06	0.42	-4.40	-307.53	0.00	-152.22	6.74	-78.52	0.57	-66.37	-0.19	8.31	-495.93	-94.92	-18.30
8	23.11.93	-1152.06	0.42	-4.40	-307.53	0.00	-152.22	6.74	-78.52	0.57	-66.37	-0.19	8.31	-495.93	-94.92	-18.30
9	30.11.93	-1152.06	0.42	-4.40	-307.53	0.00	-152.22	6.74	-78.52	0.57	-66.37	-0.19	8.31	-495.93	-94.92	-18.30
10	7.12.93	-848.00	1.54	-4.24	-278.07	0.63	-154.62	11.68	-35.46	0.57	-66.56	-0.10	15.24	-395.38	-55.61	10.68
11	14.12.93	-772.22	1.04	-4.66	-463.06	0.63	-198.89	21.81	40.71	0.57	-66.56	-0.10	14.83	-538.93	-60.25	-40.05
12	21.12.93	-822.15	0.83	-4.82	-526.80	0.63	-240.96	22.68	-21.62	0.57	-66.56	-0.10	17.76	-695.99	-100.61	-38.93
13	28.12.93	-822.15	0.83	-4.82	-526.80	0.63	-240.96	22.68	-21.62	0.57	-66.56	-0.10	17.76	-695.99	-100.61	-38.93
14	4.1.94	-934.03	0.28	-6.12	-608.61	0.63	-303.56	26.38	-83.63	0.57	-67.33	-0.10	22.89	-870.51	-127.47	-45.19
15	11.1.94	-920.88	0.33	-6.30	-620.44	0.63	-319.52	28.16	-76.10	0.57	-67.33	-0.10	25.16	-889.45	-122.13	-36.07
16	18.1.94	-1022.98	ND	ND	-642.38	0.63	-337.28	29.45	-68.98	0.57	-69.05	-0.10	26.33	-938.65	-111.86	-45.81
17	25.1.94	-1022.98	ND	ND	-642.38	0.63	-337.28	29.45	-68.98	0.57	-69.05	-0.10	26.33	-938.65	-111.86	-45.81
18	1.2.94	-901.61	ND	ND	-626.68	0.57	-332.05	39.94	23.33	0.57	-69.36	-0.10	31.59	-874.69	68.84	-36.46
19	8.2.94	-823.43	ND	ND	-640.44	0.57	-336.20	43.34	47.69	0.57	-69.94	-0.10	33.19	-844.47	106.33	-28.54
20	15.2.94	-811.23	ND	ND	-719.65	0.57	-348.14	43.27	23.58	0.57	-70.92	-0.10	32.70	-861.00	21.12	-34.97
21	22.2.94	-811.23	ND	ND	-719.65	0.57	-348.14	43.27	23.58	0.57	-70.92	-0.10	32.70	-861.00	21.12	-34.97
22	1.3.94	-653.88	ND	ND	-797.01	1.86	-366.81	47.94	-15.88	1.42	-83.73	-0.08	42.19	-932.18	-75.80	-6.70
23	8.3.94	-653.88	ND	ND	-797.01	1.86	-366.81	47.94	-15.88	1.42	-83.73	-0.08	42.19	-932.18	-75.80	-6.70
24	15.3.94	-538.57	ND	ND	-804.30	1.86	-375.21	50.86	-29.75	1.42	-97.49	-0.08	46.05	-958.53	-69.47	0.33
25	22.3.94	-383.52	ND	ND	-801.38	1.86	-379.20	53.62	-28.65	1.42	-100.34	-0.08	50.19	-960.41	-53.57	7.53
26	29.3.94	-383.52	ND	ND	-801.38	1.86	-379.20	53.62	-28.65	1.42	-100.34	-0.08	50.19	-960.41	-53.57	7.53
27	5.4.94	-298.04	ND	ND	-824.17	1.86	-388.75	58.77	-44.07	1.42	-111.80	-0.08	61.16	-994.91	-62.08	19.66
28	12.4.94	-221.28	ND	ND	-820.79	1.86	-391.63	60.32	-48.43	1.42	-113.08	-0.08	67.11	-993.44	-54.09	25.45
29	19.4.94	-221.28	ND	ND	-820.79	1.86	-391.63	60.32	-48.43	1.42	-113.08	-0.08	67.11	-993.44	-54.09	25.45
30	26.4.94	-58.12	ND	ND	-816.33	1.86	-398.24	62.95	-54.16	1.42	-122.47	-0.08	74.73	-952.50	-52.56	51.76
31	3.5.94	-58.12	ND	ND	-816.33	1.86	-398.24	62.95	-54.16	1.42	-122.47	-0.08	74.73	-952.50	-52.56	51.76
32	10.5.94	-58.12	ND	ND	-816.33	1.86	-398.24	62.95	-54.16	1.42	-122.47	-0.08	74.73	-952.50	-52.56	51.76
33	17.5.94	344.49	ND	ND	-771.37	1.88	-397.37	67.88	-36.69	3.23	-123.62	-0.03	84.22	-900.22	-11.58	94.07
34	24.5.94	344.49	ND	ND	-771.37	1.88	-397.37	67.88	-36.69	3.23	-123.62	-0.03	84.22	-900.22	-11.58	94.07
35	31.5.94	344.49	ND	ND	-771.37	1.88	-397.37	67.88	-36.69	3.23	-123.62	-0.03	84.22	-900.22	-11.58	94.07
36	7.6.94	459.61	ND	ND	-713.98	2.98	-399.93	72.94	-22.74	3.23	-124.27	-0.01	98.80	-840.88	35.88	136.09
37	14.6.94	459.61	ND	ND	-713.98	2.98	-399.93	72.94	-22.74	3.23	-124.27	-0.01	98.80	-840.88	35.88	136.09
38	21.6.94	459.61	ND	ND	-713.98	2.98	-399.93	72.94	-22.74	3.23	-124.27	-0.01	98.80	-840.88	35.88	136.09
39	28.6.94	459.61	ND	ND	-713.98	2.98	-399.93	72.94	-22.74	3.23	-124.27	-0.01	98.80	-840.88	35.88	136.09
40	5.7.94	598.78	ND	ND	-681.44	2.98	-403.15	75.48	-9.96	3.23	-125.28	0.00	104.84	-812.97	55.49	155.60
41	12.7.94	601.38	ND	ND	-679.13	2.98	-405.38	75.36	-12.79	3.23	-126.73	0.00	106.53	-816.59	54.73	158.54
42	19.7.94	601.38	ND	ND	-679.13	2.98	-405.38	75.36	-12.79	3.23	-126.73	0.00	106.53	-816.59	54.73	158.54
43	26.7.94	647.40	ND	ND	-666.33	3.05	-409.38	75.78	-12.32	3.23	-127.87	0.00	114.79	-818.52	52.87	177.92
44	2.8.94	581.70	ND	ND	-674.80	3.01	-418.01	74.41	-26.04	3.23	-128.64	-0.18	125.37	-860.46	32.38	191.30
45	9.8.94	615.68	ND	ND	-683.70	3.01	-422.37	73.29	-40.72	3.23	-129.60	-0.20	128.03	-888.30	15.36	201.48
46	16.8.94	615.68	ND	ND	-683.70	3.01	-422.37	73.29	-40.72	3.23	-129.60	-0.20	128.03	-888.30	15.36	201.48
47	23.8.94	615.68	ND	ND	-683.70	3.01	-422.37	73.29	-40.72	3.23	-129.60	-0.20	128.03	-888.30	15.36	201.48
48	30.8.94	890.17	ND	ND	-661.57	3.01	-431.43	75.55	-45.25	3.23	-130.73	-0.20	138.32	-886.32	30.74	214.59
49	6.9.94	909.35	ND	ND	-663.17	3.01	-437.14	75.25	-61.30	3.23	-133.95	-0.20	146.70	-903.46	14.14	246.14
50	13.9.94	890.96	ND	ND	-663.02	3.01	-453.43	75.20	-78.52	3.23	-134.26	-0.20	157.28	-938.07	0.55	251.06
51	20.9.94	838.67	ND	ND	-659.73	2.67	-482.35	74.87	-97.63	1.75	-137.14	-0.51	157.28	-1014.82	-23.59	255.93
52	27.9.94	854.53	ND	ND	-654.43	2.68	-487.65	75.02	-101.21	1.75	-137.21	-0.51	157.69	-1024.63	-23.09	259.52

Table A7.1 Cumulative changes in particulate matter and solutes (mg m^{-2}). ND not determined.

Week	Date	Al	Ca	Cr	Fe	K	Mg	Mn	Na	Pb	Si	Sr	V	Zn
1	5.10.93	-0.62	-5.45	-0.02	-3.04	2.14	-2.43	0.00	-3.51	0.00	-18.25	0.01	0.00	-0.20
2	12.10.93	6.45	-7.28	0.01	-5.19	3.28	-2.51	0.01	-38.29	-0.01	-3.08	0.01	0.00	-0.58
3	19.10.93	6.83	-6.59	0.00	-5.28	3.28	-3.22	0.01	-38.59	-0.02	-2.54	0.01	0.00	-0.60
4	26.10.93	6.83	-6.59	0.00	-5.28	3.28	-3.22	0.01	-38.59	-0.02	-2.54	0.01	0.00	-0.60
5	2.11.93	6.83	-6.59	0.00	-5.28	3.28	-3.22	0.01	-38.59	-0.02	-2.54	0.01	0.00	-0.60
6	9.11.93	6.83	-6.59	0.00	-5.28	3.28	-3.22	0.01	-38.59	-0.02	-2.54	0.01	0.00	-0.60
7	16.11.93	6.81	-12.69	-0.16	-17.24	9.02	-7.43	-0.20	-42.49	0.04	-32.68	-0.07	-0.19	-0.53
8	23.11.93	6.81	-12.69	-0.16	-17.24	9.02	-7.43	-0.20	-42.49	0.04	-32.68	-0.07	-0.19	-0.53
9	30.11.93	6.81	-12.69	-0.16	-17.24	9.02	-7.43	-0.20	-42.49	0.04	-32.68	-0.07	-0.19	-0.53
10	7.12.93	-4.46	-15.84	-0.30	-27.98	9.40	-10.19	-0.22	-44.03	0.04	-86.03	0.02	-0.21	-0.75
11	14.12.93	11.96	-17.85	-0.21	-29.85	13.62	-11.67	-0.10	-45.40	0.04	-90.91	0.13	-0.21	-0.79
12	21.12.93	44.71	-14.94	-0.19	-28.50	23.53	-12.02	-0.08	-46.25	0.05	-19.45	0.24	-0.21	-0.99
13	28.12.93	44.71	-14.94	-0.19	-28.50	23.53	-12.02	-0.08	-46.25	0.05	-19.45	0.24	-0.21	-0.99
14	4.1.94	65.44	-12.02	-0.18	-6.22	29.27	-9.22	0.00	-44.37	0.57	179.30	0.31	-0.21	-0.23
15	11.1.94	43.24	-13.44	-0.18	-7.70	23.43	-9.44	-0.03	-44.10	0.57	133.16	0.37	-0.21	-0.24
16	18.1.94	29.01	-11.89	-0.18	-6.27	19.90	-9.36	0.04	-43.87	0.57	105.99	0.41	-0.21	-0.09
17	25.1.94	29.01	-11.89	-0.18	-6.27	19.90	-9.36	0.04	-43.87	0.57	105.99	0.41	-0.21	-0.09
18	1.2.94	11.71	-16.29	-0.13	-10.01	19.05	-11.39	0.02	-44.35	0.58	9.20	0.46	-0.21	-0.30
19	8.2.94	-5.48	-17.97	-0.07	-15.65	19.21	-13.54	0.06	-45.09	0.58	-50.27	0.54	-0.21	-0.43
20	15.2.94	-12.03	-19.30	-0.08	-19.12	19.43	-14.60	0.01	-45.62	0.57	-77.86	0.60	-0.26	-0.47
21	22.2.94	-12.03	-19.30	-0.08	-19.12	19.43	-14.60	0.01	-45.62	0.57	-77.86	0.60	-0.26	-0.47
22	1.3.94	-56.93	-23.32	-0.18	-40.58	16.08	-19.37	-0.47	-47.21	0.57	-240.07	0.62	-0.53	-0.81
23	8.3.94	-56.93	-23.32	-0.18	-40.58	16.08	-19.37	-0.47	-47.21	0.57	-240.07	0.62	-0.53	-0.81
24	15.3.94	-88.83	-27.64	-0.11	-50.97	14.73	-23.64	-0.68	-47.99	0.57	-346.97	0.75	-0.53	-1.15
25	22.3.94	-88.83	-27.64	-0.11	-50.97	14.73	-23.64	-0.68	-47.99	0.57	-346.97	0.75	-0.53	-1.15
26	29.3.94	-115.27	-32.00	-0.02	-60.24	12.82	-26.90	-0.85	-48.71	0.56	-498.15	0.87	-0.53	-1.48
27	5.4.94	-136.42	-34.45	0.09	-64.37	13.79	-29.98	-0.81	-49.48	0.55	-622.64	1.14	-0.53	-1.83
28	12.4.94	-152.53	-35.45	0.13	-68.13	11.92	-31.43	-0.86	-49.81	0.56	-687.51	1.20	-0.53	-1.99
29	19.4.94	-152.53	-35.45	0.13	-68.13	11.92	-31.43	-0.86	-49.81	0.56	-687.51	1.20	-0.53	-1.99
30	26.4.94	-209.48	-44.02	0.11	-86.76	6.96	-37.21	-1.10	-51.00	0.60	-867.48	1.36	-0.51	-2.51
31	3.5.94	-209.48	-44.02	0.11	-86.76	6.96	-37.21	-1.10	-51.00	0.60	-867.48	1.36	-0.51	-2.51
32	10.5.94	-209.48	-44.02	0.11	-86.76	6.96	-37.21	-1.10	-51.00	0.60	-867.48	1.36	-0.51	-2.51
33	17.5.94	-262.05	-47.77	0.09	-101.20	2.30	-41.81	-1.35	-52.12	0.61	-1033.33	1.42	-0.51	-2.82
34	24.5.94	-262.05	-47.77	0.09	-101.20	2.30	-41.81	-1.35	-52.12	0.61	-1033.33	1.42	-0.51	-2.82
35	31.5.94	-262.05	-47.77	0.09	-101.20	2.30	-41.81	-1.35	-52.12	0.61	-1033.33	1.42	-0.51	-2.82
36	7.6.94	-305.85	-49.49	0.18	-115.20	-2.24	-45.31	-1.53	-53.05	0.63	-1178.66	1.49	-0.65	-3.14
37	14.6.94	-305.85	-49.49	0.18	-115.20	-2.24	-45.31	-1.53	-53.05	0.63	-1178.66	1.49	-0.65	-3.14
38	21.6.94	-305.85	-49.49	0.18	-115.20	-2.24	-45.31	-1.53	-53.05	0.63	-1178.66	1.49	-0.65	-3.14
39	28.6.94	-305.85	-49.49	0.18	-115.20	-2.24	-45.31	-1.53	-53.05	0.63	-1178.66	1.49	-0.65	-3.14
40	5.7.94	-339.96	-55.08	0.37	-124.97	-4.55	-49.38	-1.62	-56.00	0.63	-1288.92	1.53	-0.65	-3.48
41	12.7.94	-345.18	-55.18	0.55	-126.52	-4.03	-50.56	-1.64	-55.63	0.63	-1308.19	1.53	-0.65	-3.51
42	19.7.94	-345.18	-55.18	0.55	-126.52	-4.03	-50.56	-1.64	-55.63	0.63	-1308.19	1.53	-0.65	-3.51
43	26.7.94	-367.83	-59.10	0.65	-133.29	-6.53	-54.79	-1.91	-57.34	0.63	-1413.29	1.52	-0.66	-3.85
44	2.8.94	-361.71	-63.60	0.96	-131.57	-4.32	-55.00	-2.00	-66.48	0.62	-1413.32	1.43	-0.66	-4.46
45	9.8.94	-367.72	-64.22	1.14	-133.52	-4.21	-55.81	-2.00	-64.16	0.62	-1440.56	1.44	-0.66	-4.60
46	16.8.94	-367.72	-64.22	1.14	-133.52	-4.21	-55.81	-2.00	-64.16	0.62	-1440.56	1.44	-0.66	-4.60
47	23.8.94	-367.72	-64.22	1.14	-133.52	-4.21	-55.81	-2.00	-64.16	0.62	-1440.56	1.44	-0.66	-4.60
48	30.8.94	-430.32	-69.21	1.65	-151.79	-9.49	-64.90	-2.17	-68.49	0.60	-1693.43	1.46	-0.67	-5.02
49	6.9.94	-442.83	-69.09	2.22	-155.48	-9.51	-66.93	-2.25	-71.05	0.60	-1756.68	1.49	-0.67	-5.01
50	13.9.94	-473.28	-70.68	2.69	-162.39	-9.51	-72.31	-2.54	-70.93	0.59	-1881.40	1.54	-0.67	-5.09
51	20.9.94	-493.98	-74.27	2.76	-169.93	-9.51	-75.87	-2.60	-69.81	0.58	-1997.65	1.55	-0.67	-5.43
52	27.9.94	-501.66	-74.97	2.94	-172.26	-9.51	-76.92	-2.63	-68.99	0.58	-2038.44	1.55	-0.67	-5.57

Table A7.2 Cumulative elemental changes in particulate matter (mg m^{-2}).

APPENDIX 8
DATA FROM THE
SANDSTONE EXPOSURE TRIAL

	Al	Ca	Fe	K	Mg	Mn	P	S	Si	Ti	V	Zn	Zr
ST1	-4711	-78	-177	-7515	80	62	126	-424	-562	-450	12	5	-64
ST3	-4854	-252	-315	-6951	68	68	185	-191	-833	-1369	13	8	-156
ST4	-4834	-180	-647	-7358	65	48	44	-1305	2893	-645	23	9	-20
ST5	-4998	-74	-610	-7929	80	39	175	-273	2283	954	8	4	-29
ST9	-1278	-200	-494	-8894	64	32	26	-1727	632	121	3	9	101
SB1	-711	306	627	820	104	103	143	683	-17013	-1180	20	10	-311
SB3	-1366	352	900	1270	89	109	215	1042	-15720	567	30	13	-139
SB4	1019	2019	-169	1612	94	66	148	4102	-21584	1186	7	5	124
SB5	-245	735	104	1087	88	75	87	2502	-17783	533	13	8	31
SB9	-1658	2362	-769	1197	64	39	137	7078	-22779	1085	6	9	128
BT1	-4167	-48	-1160	-2752	41	16	180	-903	15154	746	4	2	93
BT3	-3904	-143	-830	-3149	41	13	811	380	4229	923	11	5	45
BT4	-5970	-278	-360	-3352	46	26	1147	618	2808	47	9	4	39
BT5	-2896	-40	-695	-4414	62	14	324	1	3290	1046	2	4	91
BT9	-2077	-135	-993	-5392	46	27	120	-621	9769	906	2	8	92
BB1	244	6183	-197	2588	89	48	229	9165	-35120	726	19	10	125
BB3	913	1469	-185	2234	84	54	280	2454	40	1026	2	5	69
BB4	333	1414	369	2822	107	54	244	1999	-7367	1088	9	2	99
BB5	1861	3230	916	2713	113	98	283	5104	-19107	1484	31	6	72
BB9	672	3637	-7	2589	101	57	135	6296	-20213	977	20	11	53
MC2	-960	-211	-1713	-5474	35	14	-8	0	7030	725	1	-5	69
MC3	-2302	-204	-1677	-5963	23	1	-34	0	5898	554	1	-22	127
MC4	-2294	-317	-1752	-7330	28	-1	-59	0	10284	580	1	-2	50
MC5	-1360	-206	-1679	-7004	23	2	-11	0	6926	518	1	0	5
MC6	-2732	-192	-1614	-7523	36	4	65	0	-325	599	1	-2	114

Table A8.1 Elemental changes (ppm).

APPENDIX 9

DATA FROM THE ANALYSIS OF SAMPLES FROM BUILDINGS

Obs.	Wea.	EF Rocks														Conc. of soluble species (% by weight)					
code	form	Al	C	Ca	Cl	Fe	K	Mg	Mn	Na	P	S	Si	V	Zr	Ca	Mg	Na	Cl	NO	SO
C1N3	GD	2.4	15.3	7.9	49.4	1.9	3.1	56.2	5.8	0.7	3.4	102.6	1.5	1.6	0.6	1.2831	0.4062	0.0938	0.2885	0.3561	5.2747
E6E6	GD	3.2	0.0	8.6	23.3	2.4	2.2	14.5	10.3	0.9	2.1	37.7	2.6	1.3	1.1	0.5473	0.0026	0.0079	0.0159	0.0211	1.1566
S1E3	GD	4.6	0.0	15.1	23.0	2.5	7.9	16.5	7.4	1.3	2.8	38.6	3.5	1.6	0.6	0.4562	0.0023	0.0113	0.0097	0.0382	0.9389
S7E6	GD	1.5	0.0	0.9	3.5	0.9	3.3	5.5	0.8	0.4	1.3	23.6	1.2	1.0	1.2	0.9727	0.0068	0.0137	0.0129	0.0578	2.3046
S1S13	MF	3.7	13.5	13.7	23.0	5.7	1.6	19.8	4.4	1.0	4.1	230.3	2.4	2.2	1.3	2.0438	0.0072	0.0209	0.0202	0.0723	4.9793
W3N2,5	MF	3.7	0.0	10.4	18.9	4.4	1.3	15.3	10.5	1.0	2.2	66.4	2.9	2.0	0.7	1.0233	0.0023	0.0109	0.0086	0.0000	2.3837
E3S16	MS	3.4	0.0	7.9	33.7	3.3	2.6	18.5	10.6	0.9	2.2	5.9	2.7	2.4	0.7	0.1156	0.0011	0.0079	0.0079	0.0000	0.2060
W3E4	MS	4.5	0.0	17.8	17.8	4.3	1.6	19.1	10.4	1.3	2.6	25.3	3.5	1.4	0.7	0.4173	0.0020	0.0070	0.0043	0.0000	0.8877
E4W3	SP	1.7	0.0	1.0	8.8	1.0	3.7	7.5	1.1	4589.6	5.5	25.5	1.2	1.5	1.0	0.5900	0.0275	0.0482	0.0646	0.1829	1.3273
C1S2	BF	4.4	69.2	22.8	68.7	3.5	4.0	25.3	5.1	1.2	8.1	492.9	2.8	3.0	0.9	1.8173	0.0072	0.0294	0.0577	0.0358	5.8829
C1W10	BF	4.2	14.4	27.0	85.5	2.8	4.9	26.4	3.3	1.2	5.2	680.8	2.1	2.0	0.1	1.9297	0.0055	0.0307	0.0689	0.0732	5.9695
C3W1	BF	1.6	4.9	0.3	13.2	1.2	4.6	4.5	1.2	0.4	2.7	6.0	1.2	1.7	0.7	0.0603	0.0073	0.0279	0.0557	0.0851	0.1241
C3N3	BF	7.0	0.0	22.4	78.2	1.6	14.8	23.8	2.2	1.9	13.4	571.6	4.3	5.6	3.0	1.9348	0.0081	0.0369	0.0496	0.1242	5.1005
E3N13	BF	5.4	0.0	43.9	24.6	3.7	4.3	36.7	4.9	6474.6	7.6	1056.0	2.5	3.0	0.6	2.1992	0.0023	0.0176	0.0227	0.0164	5.7237
E4E3	BF	3.9	0.0	31.5	62.6	1.7	11.9	26.7	2.0	18523.4	10.4	852.5	1.6	1.0	0.0	2.1829	0.0241	0.0364	0.0443	0.1677	5.6083
E6N1	BF	4.9	0.0	32.6	38.0	3.9	3.9	33.7	7.1	4345.0	7.2	728.6	2.7	2.4	0.0	2.3316	0.0227	0.0915	0.1062	0.2959	5.2966
E6E5	BF	4.2	0.0	21.9	33.6	2.9	3.1	24.8	5.5	575.9	4.6	472.5	2.6	2.1	0.6	2.4628	0.0086	0.0211	0.0286	0.0599	5.9448
S1N10	BF	4.2	0.0	27.9	42.8	2.4	3.2	25.0	6.1	5677.5	4.8	551.0	2.2	1.4	0.4	2.4905	0.0051	0.0268	0.0326	0.0847	5.7857
S7S4	BF	4.0	0.0	22.8	56.1	2.3	10.1	22.2	2.8	5443.5	9.9	589.7	1.9	1.8	0.2	2.3424	0.0285	0.0501	0.0571	0.3132	5.3131
C4E1	CF	3.3	0.0	19.0	39.5	0.9	11.8	15.2	0.8	523.8	4.6	503.9	1.7	0.1	0.6	2.3097	0.0197	0.0521	0.0782	0.3482	5.4241
S1N2	OF	4.1	0.0	21.2	30.1	3.3	2.1	19.3	10.5	1.1	6.0	346.1	2.4	1.7	0.1	2.0617	0.0090	0.0246	0.0199	0.1070	5.3913
W3N1,1	NF	4.4	0.0	21.8	30.3	3.2	2.2	20.0	9.8	1.2	4.2	323.3	2.6	1.6	1.1	2.2201	0.0039	0.0199	0.0121	0.0476	5.0542
W3W8	NF	4.0	0.0	20.7	13.3	1.8	2.2	19.7	10.6	1.1	3.4	310.8	2.5	0.1	0.8	0.0099	0.0000	0.0056	0.0028	0.0000	0.0405
C1E7	BS	5.4	0.0	36.5	59.3	2.8	5.9	35.0	3.5	1.5	9.3	914.2	2.7	1.9	0.8	2.1471	0.0070	0.0344	0.0216	0.0850	5.1207
C1N12	BS	3.0	13.7	13.8	34.7	2.0	3.1	16.6	2.9	0.8	4.0	303.4	1.8	1.1	0.4	2.3892	0.0051	0.0138	0.0141	0.1682	5.5389
C3W1	BS	2.0	8.1	0.5	8.7	1.9	4.4	6.1	1.9	0.5	3.7	12.5	1.4	2.2	1.3	1.8367	0.0169	0.0404	0.0385	0.1771	5.7867
C3S9	BS	1.5	0.0	0.2	12.1	1.2	4.6	5.5	0.9	4795.4	2.1	3.5	1.1	1.5	0.6	1.6832	0.0076	0.0180	0.0440	0.0424	5.5192
C4S5	BS	1.8	1.5	0.1	5.5	1.0	6.3	4.8	0.7	0.5	2.0	1.6	1.2	1.3	0.9	0.5108	0.0087	0.0297	0.0352	0.0562	1.3864
E4N12	BS	4.5	4.7	37.8	78.3	2.6	12.2	40.4	4.4	16965.9	7.6	853.8	2.0	1.6	0.2	0.0284	0.0019	0.0082	0.0043	0.0000	0.0844
E6N10	OS	2.4	1.4	3.5	10.3	2.3	2.1	11.8	5.3	31.6	1.7	3.4	1.9	2.0	0.6	0.0421	0.0011	0.0152	0.0045	0.0000	0.1345
E6E6	OS	5.1	0.0	20.9	29.4	4.0	3.5	21.9	16.6	4190.0	4.3	371.2	3.6	2.0	2.6	2.1529	0.0140	0.1850	0.1581	0.2176	5.4828
W3N1,8	OS	4.6	0.0	12.7	25.9	4.4	3.0	17.9	10.7	1.3	3.9	54.6	3.5	2.2	1.0	0.0468	0.0008	0.0062	0.0031	0.0000	0.0339
W4N2	OS	1.6	0.0	0.1	8.3	1.0	5.9	5.5	0.8	38.5	1.3	0.9	1.0	1.5	0.1	2.0648	0.0008	0.0085	0.0039	0.0000	4.9690
C1S4	NS	4.7	48.1	12.0	56.4	3.0	2.6	20.3	6.3	1.3	6.5	2.8	4.0	2.1	1.6	0.4705	0.0019	0.0086	0.0093	0.0000	1.0167
C1S6	NS	3.4	30.2	13.1	33.9	2.5	3.4	17.6	4.2	0.9	5.3	212.1	2.3	1.1	0.5	0.0585	0.0008	0.0084	0.0088	0.0000	0.0709
C1E3	NS	2.3	15.1	3.7	27.0	1.9	2.8	12.6	2.8	0.6	3.3	50.9	1.7	1.5	1.2	1.4741	0.0012	0.0117	0.0086	0.0000	4.5771
C1W10	NS	5.3	0.3	23.5	74.2	3.4	4.2	31.6	7.6	1.5	6.6	485.3	3.3	2.1	0.7	0.8778	0.0008	0.0107	0.0063	0.0000	2.6200
C1W11	NS	3.7	12.8	14.4	26.9	2.4	3.3	18.5	4.1	1.0	5.1	308.1	2.3	1.7	1.3	2.4336	0.0020	0.0118	0.0231	0.0121	5.4253
C3S1	NS	1.7	1.7	0.1	13.1	1.3	4.7	5.1	1.2	0.4	2.1	2.2	1.2	1.3	0.6	2.1164	0.0031	0.0193	0.0320	0.0652	4.6446
C3S7	NS	1.4	4.6	0.1	3.6	1.1	4.4	4.6	0.6	0.3	1.5	1.2	0.9	1.3	0.6	0.0331	0.0035	0.0158	0.0181	0.0484	0.0773
E3N9	NS	4.7	0.0	18.0	44.7	2.8	3.4	25.6	6.2	2782.0	4.8	403.9	3.4	1.6	1.5	0.0318	0.0038	0.0088	0.0042	0.0000	0.1063
E3N11	NS	4.0	0.0	11.7	16.3	3.3	3.0	18.1	8.0	1.1	2.4	171.7	3.0	1.8	1.5	1.7300	0.0023	0.0163	0.0054	0.0221	9.0167
E3W2	NS	4.0	0.0	10.2	33.5	3.0	2.5	18.5	6.4	1.1	2.8	134.2	3.2	1.6	2.1	1.9422	0.0008	0.0123	0.0063	0.0099	5.1210
E6E3	NS	2.8	0.0	0.6	17.6	1.8	7.3	7.6	1.7	908.6	1.8	17.3	2.1	1.4	1.0	1.2206	0.0032	0.0135	0.0131	0.0000	2.9977
W4W6	NS	1.9	0.0	0.1	2.1	1.0	6.2	6.1	0.6	2361.2	1.7	0.9	1.3	1.1	1.2	0.0772	0.0016	0.0078	0.0066	0.0000	0.2129

Table A9.1 EF Rock values and concentrations of soluble anions and cations for weathered sandstone.

APPENDIX 10

STONE SURFACE TEMPERATURES AT LICHFIELD CATHEDRAL

Date	Time	Temperature at 5mm depth (°C) N	E	S	W	Surface Temperature (°C) N	E	S	W
19/01/94	15:45	4.3	4.1	7.7	7.1				
19/01/94	16:00	4.3	4.1	7.1	6.5				
19/01/94	16:15	4.1	3.8	6.3	5.8	4	4	6	6
19/01/94	16:30	4.0	3.8	5.8	5.4	4	4	6	5
19/01/94	16:45	3.8	3.6	5.4	4.9				
19/01/94	17:00	3.6	3.3	4.9	4.5				

Table A10.1 A comparison between stone temperatures at 5 mm depth measured with thermistors to an accuracy of 0.1°C and surface temperatures measured with an infrared thermometer to an accuracy of 1.0°C.

REFERENCES

AGRAWAL, O. *et al.* (1986) Study and conservation of spotted red sandstone of Mathura. IN BROMMELLE, N and SMITH, P. *Case studies in the conservation of stone and wall paintings.* 165-169.

ALLEN, G. (1929) *Indusrial Development Birmingham and the Black Country 1860-1927.* Allen & Unwin, London.

ALLEN, W (1946) *The Black Country.* Paul Elek, London.

AMERICAN GEOLOGICAL INSTITUTE. (1960) *Glossary of geology and related sciences.* Washington D. C. (Supplement).

AMOROSO, G. and FASSINA, V. (1983) Stone decay and conservation. *Materials science monographs,* **11**. Elsevier, Oxford.

ANSTED, D. (1871) On some phenomena of the weathering of rocks, illustrating the nature and extent of subaerial denudation. *Transactions of the Cambridge Philosophical Society.* **11**, 387-395.

ASHTON, H. and SEREDA, P. (1982) Environment, microenvironment and durability of building materials. *Durability of Building Materials.* **1**, 49 - 65.

BERNARDI, A. *et al.* (1985) Microclimate and Weathering of a Historical Building: The Ducal Palace in Urbino. *The Science of the Total Environment.* **46**, 243-260.

BIGGS, W. (1994) Fracture. IN ILLSTON, J. (Ed.) *Construction Materials - Their Nature and Behaviour (2nd Ed.).* Chapter 6, 39-43. E and F Spon, London.

BLACKWELDER, E. (1933) The insolation hypothesis of rock weathering. *American Journal of Science*, **226**, 97-113.

BLUCK, B. (1992) The composition and weathering of sandstone with relation to cleaning. IN WEBSTER, R. (Ed.) (1992) *Stone Cleaning and the Nature, Soiling and Decay Mechanisms of Stone: Proceeding of the International Conference,* 14-16 April 1992, Edingburgh, UK, Donhead, London, UK. 125-127.

BLUCK, B. and PORTER, J. (1991a) Sandstone buildings and cleaning problems. *Stone industries*, **26** (2), 21-27.

BLUCK, B. and PORTER, J. (1991b) Aims and methods of sandstone cleaning. *Stone industries*, **26** (3), 21-28.

BOCK, E. and SAND, W. (1993) A Review: The Microbiology of Masonry Biodeterioration. *Journal of Applied Bacteriology.* **74**, 503-514.

BOS, K. and GULLENTOPS, F. (1990) Ijzerzandsteen als bouwsteen in en rond het Hageland. *Bull. Belg. Ver. vr. Geol.* 99, 131-151.

BRIDGMAN, P. (1912) Water in the liquid and five solid forms, under pressure. *Proceedings of the Academy of Arts and Science*, **47**, 439-558.

BRITISH STANDARDS INSTITUTION (BSI,) (1992) Code of practice for assessing exposure of walls to wind driven rain. *BS 8104 : 1992.*

BROWN, C. (1924) On some effects of wind and sun in the desert of Tumbez, Peru. *Geological Magazine*, **61**, 337-339.

BRUGGERHOFF, S. and MIRWALD, P. (1992) Examination of complex weathering processes of different materials by field exposure studies. IN RODRIGUES, J. *et al.* (Eds.)

7th International Congress on Deterioration and Conservation of Stone, Lisbon, Portugal, 15-18 June 1992. 715-726.

BUILDNG RESEARCH ESTABLISHMENT (1979) Estimation of thermal and moisture movements and stresses: Part 2. *Building Research Establishment Digest 228.*

BURDINE, N. (1963) Rock failures under dynamic loading conditions. *Soc. Pet. Eng. J.*, 1-8

CANEVA, G. *et al.* (1992) Incident rainfall in Rome and its relation to biodeterioration of buildings. *Atmospheric Environment.* 26B (2), 255-259.

CHARSLEY, T. (1982) *A standard nomenclature for the Triassic formation of the Ashbourne district.* Report of the Institute of Geological Sciences, No. 81/14.

CHENG, R., *et al.* (1976) Characterization of Particulates from Power Plants. *Journal of Air Pollution Control Association.* 26 (8), 787-790.

CIABACH, J. and SKIBINSKI, S. (1989) Analyses of the total salt content and control of salt removal from stone historical objects. IN ZEZZA, F. (Ed.) *The Conservation of Monuments in the Mediteranean Basin. Proceedings of the 1st International Symposium,* Bari, Italy, 7-10 June 1989.

COLMAN, S. (1982) *Chemical Weathering of Basalts and Andesites: Evidence from Weathering Rinds.* United States Government Printing Office, Washington.

COOKE, R. and GIBBS, G. (1995) *Crumbling Heritage? Studies of Stone Weathering in Polluted Atmospheres.* National Power plc, Swindon.

COOPER, T. *et al.* (1992) Rates of Deterioration of Portland Limestone in an Urban Environment. *Studies in Conservation,* **37**, 228-238.

DOMONE, P. (1994) Concrete. IN ILLSTON, J. (Ed.) *Construction Materials - Their Nature and Behaviour (2nd Ed.)*. Part 3, 87-196. E and F Spon, London.

ELFVING, P. *et al.* (1994) Model study of the first steps in the deterioration of calcareous stone: III. Manganese and iron mediated sulphation of natural stone. *Applied Surface Science*, 78, 373-384

EVERETT, A. (1986) *Materials*. Longman Scientific and Technical, Harlow.

EVERITT, B. (1980) *Cluster Analysis (2nd Ed.)*. Heinemann, London.

FASSINA, V. (1992) The degradation of the portal of the Basilica of SS Giovanni E Paolo in Venice IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone*, Lisbon, Portugal, 15-18 June 1992. 119-128.

FASSINA, V. and STEVAN, A. (1992) Microclimatic survey in S. Maria Dei Miracoli Church in Venice in relation to marble decay. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone, Volume 1*, Lisbon, Portugal, 15-18 June 1992, pp 355-365.

FAY, A. (1920) A glossary of the minning and mineral industry. *BuMines Bulletin*, 95.

FITZNER, B. *et al.* (1992) Classification and Mapping of Weathering Forms. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone, Volume 2*, Lisbon, Portugal, 15-18 June 1992, pp 957-968.

FOBE, B. *et al.* (1993) Weathering of Miocene Ferruginous Sandstone in ancient buildings in Northeastern Belgium. *The science of the total environment.* 132, 53-70

GALAN, E. *et al.* (1992) Progressive deterioration of marble columns by thermal changes in relation to their state of superficial decay. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone,* Lisbon, Portugal, 15-18 June 1992. 905-913.

GEIKE (1880) Rock weathering as illustrated in Edinburgh church yards. *Proceedings of the royal society of Edinburgh*, 10, 518-532.

GORBUSHINA, A. *et al.*, (1993) Role of black fungi in color change and biodeterioration of antique marbles. *Geomicrobiology Journal*, 11 (4), 205-221.

GOUDIE, A. (1985) *Salt weathering.* Research paper 33. School of geography, University of Oxford.

GRAY, W. (1965) Surface spalling by thermal stresses in rocks. IN *Proceedings rock mechanics symposium,* Toronto 85-106.

GRIGGS, D. (1936) The factor of fatigue in rock exfoliation. *Journal of Geology*, 44, 783-796.

HAIMSON, B. (1974) Mechanical behaviour of rock under cyclic loading. IN. *Proceedings of the 3rd congress of the International Association for Rock Mechanics, Volume 2.* Denver, National Academy Science, Washington. 373-378.

HALL, C. and KALIMERIS, A. (1982) Water movement in porous building materials - V. Absorption and shedding of rain by building surfaces. *Building and environment.* 17 (4), 257-262.

HALSEY, D., *et al.* (1995a) Real-time measurements of sandstone deterioration: A microcatchment study, *Building and Environment.* 30 (3), 411-417.

GALAN, E. *et al.* (1992) Progressive deterioration of marble columns by thermal changes in relation to their state of superficial decay. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone,* Lisbon, Portugal, 15-18 June 1992. 905-913.

GEIKE (1880) Rock weathering as illustrated in Edinburgh church yards. *Proceedings of the royal society of Edinburgh*, 10, 518-532.

GORBUSHINA, A. *et al.*, (1993) Role of black fungi in color change and biodeterioration of antique marbles. *Geomicrobiology Journal*, 11 (4), 205-221.

GOUDIE, A. (1985) *Salt weathering.* Research paper 33. School of geography, University of Oxford.

GRAY, W. (1965) Surface spalling by thermal stresses in rocks. IN *Proceedings rock mechanics symposium,* Toronto 85-106.

GRIGGS, D. (1936) The factor of fatigue in rock exfoliation. *Journal of Geology*, 44, 783-796.

HAIMSON, B. (1974) Mechanical behaviour of rock under cyclic loading. IN. *Proceedings of the 3rd congress of the International Association for Rock Mechanics, Volume 2.* Denver, National Academy Science, Washington. 373-378.

HALL, C. and KALIMERIS, A. (1982) Water movement in porous building materials - V. Absorption and shedding of rain by building surfaces. *Building and environment.* 17 (4), 257-262.

HALSEY, D., *et al.* (1995a) Real-time measurements of sandstone deterioration: A microcatchment study, *Building and Environment.* 30 (3), 411-417.

HALSEY, D., *et al.* (1995b) The effects of atmospheric pollutants upon sandstone: Evidence from real-time measurements and analysis of decay features on historic buildings. IN KAMARI, J., *et al.* (Eds) *Proceedings of the 10th World Clean Air Congress, Volume 3, Espoo, Finland, 28 May - 2 June*, FAPPS, Helsink.

HALSEY, D., *et al.* (1996) The black soiling of sandstone buildings in the West Midlands, England: Regional variations and decay mechanisms. IN SMITH, B. and WARKE, P. *Processes of urban stone decay.* Chapter 5, 53-65, Donhead Publishing, London.

HEATING AND VENTILATION COMMITTEE OF THE BUILDING RESEARCH BOARD (1945) *Heating and Ventilation of Dwellings.* Her Majesties Stationary Office, London.

HENRIKSEN, J. *et al.* (1993) Monitoring of the wetness impact on buildings by means of a new instrument for continous recordings. IN THIEL, J. (Ed) *Conservation of stone and other material.* Vol. 2. 784-791. E & FN Spon, London.

HIRSCHWALD, J. (1908) *Die Prufung der Naturlichen Bausteine auf ihre Wetterbestandigkeit.* Berlin.

HOCKMAN, A. and KESSLER, D. (1950) *Thermal and moisture expansion studies of some domestic granites. U. S. department of commerce national bureau of standards.* RP 2087, 44, 395-410.

HONEYBORNE, D. and HARRIS, P. (1958) The structure of porous building stone and it's relation to weathering behaviour. IN EVERETT, D. and STONE, F. (Eds) *The structure and properties of porous materials* (Proceedings of the tenth symposium of Colston research society). Butterworths, London. 343-366.

HOWARD, P. (1991) *An Introduction to Environmental Pattern Analysis.* The Parthenon Publishing Group, New Jersey.

HUDEC, P. and RIGBEY, S. (1976) The effects of sodium chloride on water sorption characteristics of rock aggregate. *Bulletin of the association of engineering geologists*, **13** (3), 199-211.

HUECK-VAN DER PLAS, (1968) The micro-biological deterioration of porous building materials. *International biodeterioration bulletin*, 4 (1), 11-28.

HUNT, D. and WILSON, A. (1986) *The chemical analysis of water. (2nd Ed)*. Royal Society of Chemistry, London.

INKPEN, R. (1989) *Stone decay and atmospheric pollution in a transect across Southern Britain.* PhD Thesis University College London.

JAYNES, S. (1985) *Studies of building stone weathering in S. E. England.* PhD Thesis University College London.

JEFFREY, D. *et al.* (1985) A test-rig for determining short term weathering rates of building materials under urban environmental conditions.IN *The effects of air pollution on historic buildings and monuments.* Padua 30/9-2/10/85. p83-95.

JENKINS, K. and SMITH, B. (1990) Daytime rock surface temperature variability and its implications for mechanical rock weathering: Tenerife Canary Islands. *Catena*, **17**, 449-459.

JOHNSON, W. and PARSONS, W. (1944) Thermal exapnsion of concrete aggregate materials. *Journal of Research NBS*, **32**, 101.

JONES, D. and WILSON, M. (1985) Chemical activity of lichens on mineral surfaces - A review. *International biodeterioration.* **21** (2), 99-104.

KELLER, W. (1957) *The Principles of Chemical Weathering*. Lucas Brothers, Columbia.

KOZU and SAIKI, (1925) Sci. Rep. Toh. Univ. **3** (2), 205. As quoted in the Handbook of Physical Constants (1933). *Geological Society of America Special Papers*, **26** (33).

KRUMBEIN, W. (1992) Colour changes of building stones and their direct and indirect biological causes. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone*,Lisbon, Portugal, 15-18 June 1992. 443-452.

LEARY, E. (1986) *The building sandstones of the British Isles.* Building Research Establishment, HMSO.

LEYSEN, L. *et al.* (1987) Classification of suspended particles in deposition samples and run off water samples from a limestone cathedral. *Atmospheric environment.* **21** (11) 2425-2433.

LEYSEN, L. *et al.* (1989) Air pollution induced chemical decay of a sandy - limestone cathedral in Belgium. *The science of the total environment*, **78**, 263-287.

LIVINGSTON, R. *et al.*. (1983) *Stone deterioration studies at Bowling Green Custom House*, Interim report 1981. EPA 600/6-84-003. NTIS. Springfield.

LLOPIS, V. *et al.* (1992) Conditions that influence the position and crystallization of salts. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone*,Lisbon, Portugal, 15-18 June 1992. 895-904.

LOFVENDAHL, R. (1992) Weathering of stone. IN GULLMAN, J. (Ed) *Air Pollution and the Swedish Heritage: Progress 1988-1991.* Riksantikvarieambetet, Sweden. 15-20.

LOFVENDAHL, R. *et al.* (1992) Building stone and sculptural decorations. IN GULLMAN, J. (Ed) *Air Pollution and the Swedish Heritage: Progress 1988-1991.* Riksantikvarieambetet, Sweden. 51-99.

MALESANI, P. and VANNUCCI, S. (1974) Decay of Pietra Serena and Pietraforte, Florentine building stones : Petrographic observations. *Studies in conservation*, 19, 36-50.

MARTINO-PATINO, M. *et al.* (1992) Characterisation of the sandstone of Salamance Cathedrals. Forrms of weathering. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone,* Lisbon, Portugal, 15-18 June 1992. 315-324.

MASONRY CONSERVATION RESEARCH GROUP, THE ROBERT GORDON INSTITUTE OF TECHNOLOGY, ABERDEEN (1992) *Stone Cleaning in Scotland: Research Commission Iinvestigating the Effects of Cleaning of Sandstone. Research Summary.* Historic Scotland, Scottish Enterprise and The Robert Gorden Institue of Technology, Aberedeen.

McGREEVY, J. (1981) *Some perspectives on frost shattering. Progress in Physical Geography.* **5** (1), 56-75.

McGREEVY, J. (1985a) Thermal properties as controls on rock surface temperature maxima, and possible implications rock weathering, *Earth Surface Processes and Landforms.* **10,** 125-136.

McGREEVY, J. (1985b) A preliminary scanning electron microscope study of honeycomb weathering of sandstone in a coastal environment. *Earth surface processes and landforms.* **10,** 509-518.

MORRIS, R. and FLETCHER, A. (1987) Increased solubility of quartz following ferrous-ferric iron reactions. *Nature*, 330 (6148), 558-561.

MOSES, C. (1994) *The Origin and Implications of Microsolutional Features on the Surface of Limestone*. PhD Thesis, The Queen's University of Belfast.

MOTTERSHEAD, D. (1994) Spatial variations in the intensity of alveolar weathering of a dated sandstone structure in a coastal environment, Weston-super-Mare, UK. IN ROBINSON, D. and WILLIAMS, R. (Eds.) *Rock Weathering and Landform Evolution*. J. Wiley & Sons, Chichester, pp 157-174.

NORD, A. and TRONNER, K. (1992) Characterisation of thin black layers. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone*,Lisbon, Portugal, 15-18 June 1992. 217-226.

O'BRIEN, P. *et al.* (1991) Time series analysis of anions and cations in runoff from daily washed and unwashed new limestone catchments at trinity college dublin during june 1989. IN BAER. N. *et al. Science, technology and european cultural heritage*, Bologna 13-16/6/93.

OKE, T. (1990) *Boundary layer climates (2nd Ed.)*. Routledge, London.

OLLIER, C. (1984) *Weathering (2nd Ed)*. Longman, London.

ORTEGA-CALVO, J *et al.* (1992) Experimental stratergies for investigating algal deterioration of stone. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone*,Lisbon, Portugal, 15-18 June 1992. 541-550.

O'NEILL, H. (1965) *Stone for Building*. Heinemann, London.

O'NEILL, P. (1993) *Environmental Chemistry (2nd Edition)*. Chapman and Hall, London.

OXLEY, T. and GOBERT, E. (1983) *Dampness in Buildings*. Butterworths, London.

PALMER, R. *et al.* (1991) Biomass and organic acids in sandstone of a weathered building: Production by bacterial and fungal isolates. *Microbial Ecology* **21**, 253-266.

PETTIJOHN, F. (1963) Chemical composition of sandstones - excluding carbonates and volcanic sands. *US Geological Survey Professional Paper*, 440-S.

PETTIJOHN, F. et al. (1972) *Sand and Sandstone*. Springer-Verlag, Berlin.

PEVSNER, N. (1958) *The Buildings of England: Shropshire.* Penguin Books, Harmondsworth.

PEVSNER, N. (1968) *The Buildings of England: Worcestershire.* Penguin Books, Harmondsworth.

PEVSNER, N. (1974) *The Buildings of England: Staffordshire.* Penguin Books, Harmondsworth.

PEVSNER, N. and WEDGWOOD, A. (1966) *The Buildings of England: Warwickshire.* Penguin Books, Harmondsworth.

POTTS, P. (1987) *A handbook of silicate rock analysis.* Blackie, London.

PUHRINGER, J. *et al.* (1992) Deterioration of Gotland Sandstone at the Royal Palace, Stockholm . IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone,* Lisbon, Portugal, 15-18 June 1992. 687- 695.

ROBINSON, D. and WILLIAMS, R. (1992) Sandstone Weathering in the High Atlas, Morocco. *Zeitschrift Geomorphologie*, **36, (4)**, 413-429.

ROBINSON, D. and WILLIAMS, R. (1994a) Sandstone weathering and landforms in Britain and Europe. IN ROBINSON, D. and WILLIAMS, R. (Eds.) *Rock Weathering and Landform Evolution.* J. Wiley & Sons, Chichester, pp 371-392.

ROBINSON, D and WILLIAMS, R (1994b) Advances in rock weathering. IN ROBINSON, D. and WILLIAMS, R. (Eds.) *Rock Weathering and Landform Evolution.* J. Wiley & Sons, Chichester, pp xv-xxi.

ROENICKE, U. and ROENICKE, R. (1972) Uber den Mechanismus der zerstoerendum Wirkung der Luftverunreinigung am Frieburger Muenster. *Deutch Kunst und Denkmalpflege*. 30, 57-64

ROSSA, R. and SILVA, O. (1992) Alteration of igneous rocks by thermo-mechanical loads. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone*,Lisbon, Portugal, 15-18 June 1992. 651-658.

SABBIONI, C. and ZAPPIA, G. (1992) Decay of sandstone in urban areas correlated with atmospheric aerosol. *Water, Air and Soil Pollution.* 63, 305-316.

SCHAFFER, R. (1932) *The weathering of natural building stones.* London, HMSO.

SEREDA, P. (1974) Weather factors effecting the corrosion of metals. IN *Corrosion in Natural Environments*, ASTM STP 558, 7-22.

SHARP, A. *et al.* (1982) Weathering of the balustrade on St. Pauls Cathedral, London. *Earth Surface Processes and Landforms*. 7, 387-389.

SIEGEL, R. and HOWELL, J. (1972) *Thermal Radiation and Heat Transfer.* McGraw-Hill, New York.

SMITH, B. and McALISTER, J. (1986) Observations on the occurrence and origins of salt weathering phenomena near Lake Magadi, southern Kenya. *Zeit. fur Geomorph*, 30, 445-460.

SMITH, B. and McGREEVY, J. (1988) Contour scaling of a sandstone by salt weathering under simulated hot desert conditions. *Earth Surface Processes and Landforms*, **13**, 697-705.

SMITH, B. *et al.* (1987) Silt production by weathering of sandstone under hot arid conditions : An experimental study. *Journal of arid environments*, **12**, 199-214.

SMITH, B. *et al.* (1991a) Stone decay in a 'clean' environment: Western Northern Ireland. IN BAER, N. *et al.* (Eds.) (1991) *Science, Technology and European Cultural Heritage: Proceedings of the European Symposium, Bologna, Italy,* 13-16 June 1989. Butterworth-Heinemann, Oxford, UK, 434-438.

SMITH, B. *et al.* (1991b) Background and local contributions to acidic deposition and their relative impact on building stone decay: A casestudy of Northern Ireland. IN LONGHURST, J (Ed.) (1991) *Acid Deposition: Origins, Impacts and Abatement Strategies*. Springer-Verlag, Berlin. 241-265.

SMITH, B. *et al.* (1992) Assessment of building stone decay: a geomorphological approach. IN WEBSTER, R. (Ed.) (1992) *Stone Cleaning and the Nature, Soiling and Decay Mechanisms of Stone: Proceeding of the International Conference,* 14-16 April 1992, Edingburgh, UK, Donhead, London, UK. 249-257.

SMITH, B. *et al.* (1994) Breakdown patterns of quartz sandstone in a polluted urban environment: Belfast, N. Ireland. IN ROBINSON, D. and WILLIAMS, R. (Eds.) *Rock Weathering and Landform Evolution.* J. Wiley & Sons, Chichester, pp 131-150.

SRAMEK, J. (1992) Kaolinitic quartz sandstones - the influence of mineralogy on physical - mechanical properties and durability, IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone,* Lisbon, Portugal, 15-18 June 1992. 67- 77.

STEIGER, M. *et al.* (1993) Deposition and enrichment of atmospheric pollutants on building stones as determined by field exposure experiments. IN THIEL, J. (Ed) *Conservation of stone and other material.* Vol. 1. 35-42. E & FN Spon, London.

STUMM, W. and MORGAN, J. (1981) *Aquatic Chemistry (2nd Ed.).* John Wiley and Sons, New York.

STUTTARD, R. (1992) *Data: Collection, presentation, initial analysis and exploration (2nd Ed.).* Erithacus Press, Wolverhampton.

SWEEVERS H. and VAN GRIEKEN, R. (1992) Analytical study of the deterioration of sandstone, marble and granite. *Atmospheric Environment,* 26B (2), 159-163.

TAKAHASHI, K. *et al.* (1994) Erosion rates of a sandstone used for a masonry bridge pier in the coastal spray zone. IN ROBINSON, D. and WILLIAMS, R. (Eds.) *Rock Weathering and Landform Evolution.* J. Wiley & Sons, Chichester, pp 175-192.

THRELKELD, J. (1970) *Thermal Environmental Engineering (2nd Ed.).* Prentice Hall, New Jersey.

TWILLEY, J. and PODANY, J. (1986) Deterioration of Arizona Red Sandstone and refinement of methods for its treatment. IN BROMMELLE, N and SMITH, P *Case studies in the conservation of stone and wall paintings.* 174-179.

VERHOEF, L. (1988) Soiling and Cleaning of Building Facades: Report of the Technical Committee 62 SCF RILEM. Chapman and Hall, London.

VELDE, B. (1992) *Introduction to clay minerals*. Chapman and Hall, London.

VENDRELL-SAZ, M. and GARCIA-VALLES, M. (1992) Decay mechanisms of the romanesque portal of Ripoli. IN RODRIGUES, J. *et al.* (Eds.) *7th International Congress on Deterioration and Conservation of Stone*, Lisbon, Portugal, 15-18 June 1992. 277-286.

VILES, H. (1993) The environmental sensitivity of blistering of limestone walls in Oxford, England: A preliminary study. IN THOMAS, D. and ALLISON, R. (Eds.) *Landscape Sensitivity*. John Wiley and Sons, Chichester. 309-326.

VLEUGELS, G. *et al.* (1992) Analytical study of the weathering of the Jeronimos Monastery in Lisbon. *The Science of the Total Environment.* 120, 225-243.

WARKE, P. and SMITH, B. (1994) Short-term rock temperature fluctuations under simulated hot desert conditions: Some preliminary data. IN ROBINSON, D. and WILLIAMS, R. (Eds.) *Rock Weathering and Landform Evolution.* J. Wiley & Sons, Chichester, pp 57-70.

WARKE, P. *et al.* (1996) Thermal response characteristics of stone: Implications for weathering of soiled surfaces in urban environments. *Earth Surface Processes and Landforms*, **21**, 295-306.

WARREN SPRING LABORATORY (1973) *National Survey of Air Pollution 1961-71: Volume 3*. HMSO, London.

WENDLER, E. *et al.* (1990) Contour scaling on building facades - dependence on stone type and environmental conditions. IN *Analytical methodologies for the investigation of damaged stones.* Pavia, 14-21/9/90.

WEST MIDLANDS GROUP (1948) *Conurbation: A planning survey of Birmingaham and the Black Country.* The Architectural Press, London.

WHALLEY, W. *et al.* (1992) Short-term exposure of limestone test specimens in Venice. IN RODRIGUES,J. *et al.* (Eds) *The 7th International congress on deterioration and conservation of stones.* Lisbon, Portugal 15-18 June 1992. 287-297.

WILLIAMS, R. and ROBINSON, D. (1981) Weathering of sandstone by the combined action of frost and salt. *Earth Surface Processes and Landforms,* 6, 1-9.

WILLIAMS, R. and ROBINSON, D. (1994) Weathering flutes on siliceous rocks in Britain and Europe. IN ROBINSON, D. and WILLIAMS, R. (Eds.) *Rock Weathering and Landform Evolution.* J. Wiley & Sons, Chichester, pp 413-432.

WILLS, L. (1970) Geology. IN *Birmingham and its Regional Setting: A Scienfiic Survey.* S R Publishers Ltd., Wakefield, pp 15-36.

WINKLER, E. (1987) Weathering and weathering rates of natural building stone. *Enviromental Geology and Water Science*, 9 (2), 85-92.

WINKLER, E. and SINGER, P. (1972) Crystallisation pressure of salts in stone and concrete. *Geological Society of America Bulletin.* 83, 3509-3514.

YATSU, E. (1966) *Rock Control in Geomorphology.* Sozosha, Tokyo.

YATSU, E. (1988) *The nature of rock weathering.* Sozosha, Tokyo.

YOUNG, A. (1987) Salt as an agent in the development of caverous weathering. *Geology,* 15, 962-966.

YOUNG, R. and YOUNG, A. (1992) *Sandstone Landforms.* Springer-Verlag, Berlin.

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Real Time Measurements of Sandstone Deterioration: a Microcatchment Study

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In order to gain a greater insight into the mechanisms responsible for the deterioration of sandstone buildings, chemical analysis of runoff water from sandstone and glass (control) surfaces has been carried out. Results indicate that the blocking of the stone's pores by atmospheric particulates, soluble salts and algae may be involved in this decay. Evidence is presented which indicates that pressures created by salts and trapped moisture may cause the detachment of surface layers of sandstone from buildings. Weakening by kaolinite formation is identified as a potential factor in sandstone weathering.

INTRODUCTION

SANDSTONE is extensively used as a building material in Great Britain, especially in areas where suitable reserves of sandstone exist or have existed in the past. Due to different geological sources, sandstones vary greatly in appearance and durability. However, the dominant mechanisms involved in their deterioration are often similar. In many cases the weathering of surface layers of stone produces a crust, which eventually detaches from the stone. Widespread detachment causes a material loss as well as altering the aesthetic values of buildings as crusts are often different in colour from the original sandstone.

Crust formation can be caused by several factors, depending on the properties of the sandstone and the environmental conditions. Crusts can develop due to the deposition of atmospheric particles onto the surface of the stone [1], biological activity [2] or the dissolution of materials from within the stone. This dissolved material precipitates at the surface of the stone as it dries [3]. In sandstones with very little soluble material, other components of the building fabric (e.g. mortar or limestone) may provide the solutes to form crusts [4]. Once a crust has formed, detachment may result from a lack of adhesion, due to the dissolution of natural cementing materials beneath the crust [3]. Alternatively, detachment can be caused by reactions behind the crust created by trapped moisture [5], such as salt crystallisation and hydration processes [6] or the expansion and contraction of clays [7].

Many processes involved in crust formation cause the crust to have a different chemical composition from the underlying sandstone [3]. Analysis of unweathered stone and other constituents of the building fabric can indicate the origin of these chemical changes. However, the provenance of some elements is by no means conclusive and hence the processes of crust formation cannot be ascertained accurately. A current research project at the University of Wolverhampton aims to examine the influence of environmental factors upon the deterioration of sandstone buildings. As part of this programme, real time monitoring of sandstone weathering is being undertaken.

THE MICROCATCHMENT TECHNIQUE

To measure the weathering of sandstone over short periods of time, microcatchments have been constructed. Much of the development of the microcatchment technique was carried out on slabs of Portland Limestone in Dublin [8]. In this investigation six microcatchments were constructed as shown in Fig. 1. Three were fitted with 50

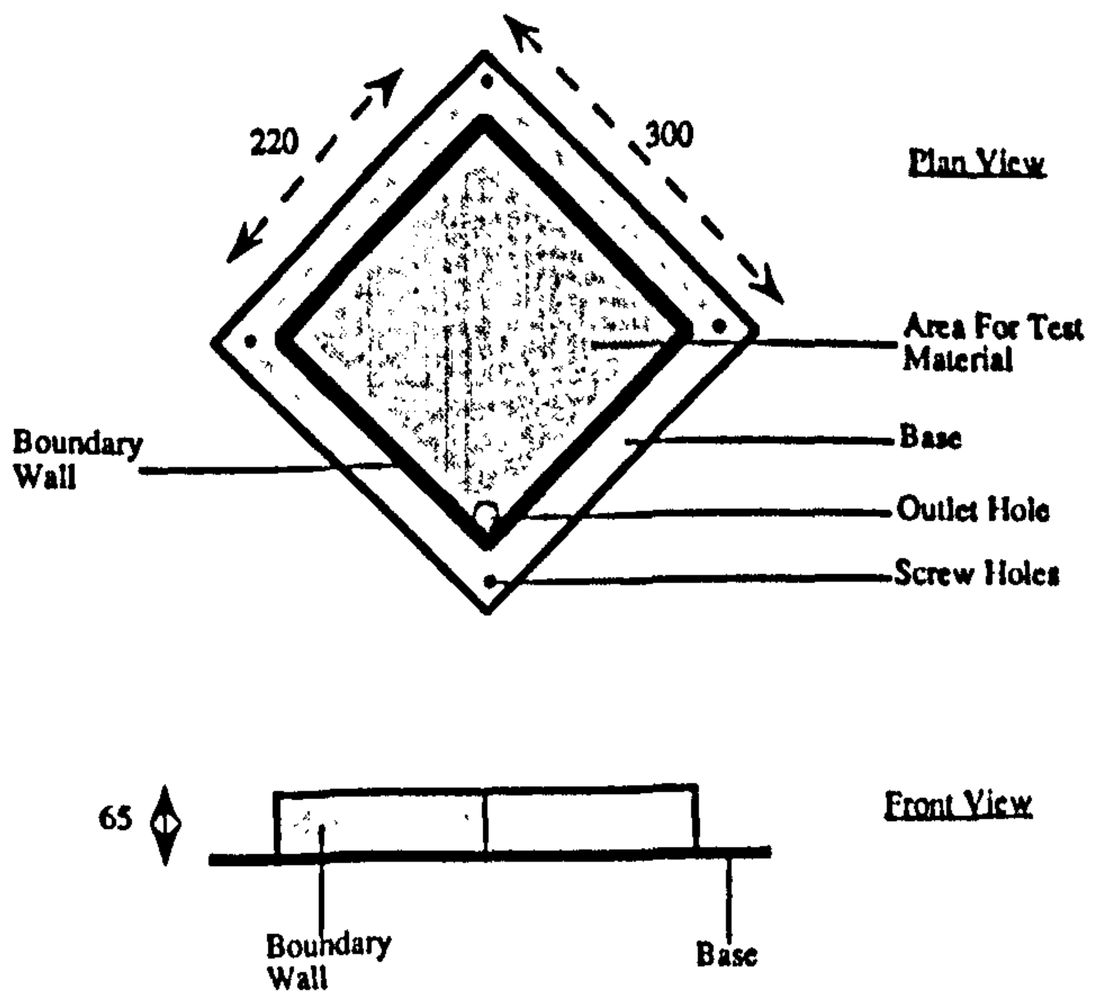

Fig. 1. Microcatchment design (all dimensions in mm).

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Table 1. Composition of Mottled Hollington Sandstone expressed as per cent oxide (by weight)

Composition	Concentration
Aluminium (Al_2O_3)	7.2850
Barium (BaO)	0.0539
Calcium (CaO)	0.0606
Chromium (Cr_2O_3)	0.0856
Iron (Fe_2O_3)	1.4296
Magnesium (MgO)	0.9634
Manganese (MnO)	0.0249
Nickel (NiO)	0.0329
Phosphorus (P_2O_5)	0.0506
Potassium (K_2O)	2.4119
Rubidium (Rb_2O)	0.0265
Silicon (SiO_2)	86.2279
Sodium (Na_2O)	0.2507
Titanium (TiO_2)	0.1447
Total	99.0482

mm thick slabs of Mottled Hollington Sandstone. The slabs were cut from a single block of stone using a water cooled diamond saw. They were placed in the microcatchments and their sides sealed with silicon sealant, to prevent water seepage down the edges of the stone. Mottled Hollington Sandstone, a medium grained ferruginous Triassic Sandstone, was selected because it is widely used in central England, including some notable buildings such as Coventry Cathedral. The stone was obtained from J. Oldham Ltd, Great Gate Quarry, Staffordshire. Its chemical composition was determined using a Fisons ARL 8410 X-Ray Fluorescence Spectrometer (XRF) (Table 1).

As a control, three microcatchments were fitted with a glass surface. The 4 mm glass plates were first roughened by sandblasting and then glued to a polystyrene slab, to make a total thickness of 50 mm (the same as the sandstone slabs). Glass was used as a control surface because previous research [9] found it to be more suitable than either perspex or copper surfaces. Tests for water solubility were carried out on some of the materials used to construct the microcatchments, by shaking two grams in distilled water. Subsequent multi-element analysis of the leachate using a Thermo Jarrell Ash Plasma-300 Inductively Coupled Plasma Spectrometer (ICP) suggested these materials would not interfere with the experiment (Table 2).

The six microcatchments were installed at the University Urban Meteorological Station, which is a roof top site in Wolverhampton town centre (Fig. 2). The microcatchments were attached to the south west facing parapet at a fifteen degree angle to the horizontal, with the corner housing the plastic discharge tube at the lowest point. The parapet was covered with 'Astro Turf' to reduce contamination by raindrop splash. The stone and glass units were arranged alternatively and the discharge tube from each unit was fed to an individual polyethylene bottle through a water tight seal. The collecting bottles were housed in an insulated box, in order to reduce algae growth, to minimise changes in sample temperature, which could otherwise affect solubility, and to limit sample evaporation, which would increase the concentration of the solution.

Runoff from the microcatchments was collected weekly, provided that at least 50 ml of runoff had occurred. The volume and pH were measured and the samples filtered in preparation for chemical analysis. Whatman Cellulose Nitrate membrane filters with a 0.45 μm pore size were found to be most suitable [10]. The filtrates were analysed for chloride, sulphate and nitrate anions, using a Dionex DX-100 Ion Chromatograph, while potassium was determined with a Varian AA-75 Atomic Absorption Spectrometer. Twelve other elements were determined using a Thermo Jarrell Ash Plasma-300 Inductively Coupled Plasma Spectrometer (ICP). The filter membranes were dried and semi-quantitative elemental analysis carried out on selected samples using a Fisons ARL 8410 X-Ray Fluorescence Spectrometer (XRF).

In order to assess the differences between the sandstone and the control microcatchments, cumulative losses and gains have been calculated (in mg m^{-2}) for particulate and chemical species under consideration (Figs 3–7). These were derived from subtracting the weekly values obtained for the three glass microcatchments from those obtained for the three sandstone microcatchments to give three results in milligrammes. These were averaged and multiplied by 20.66 to standardise them to a sandstone slab one metre square and five centimetres thick [equation (1)]. The results for each week were then added to those of the previous weeks to give cumulative losses and gains.

$$\text{Weekly value } (\text{mg m}^{-2}) = \left[\frac{(\text{stone 1} - \text{control 1}) + (\text{stone 2} - \text{control 2}) + (\text{stone 3} - \text{control 3})}{3}\right] * 20.66. \quad (1)$$

Table 2. Amount of water soluble material contained in the microcatchment construction materials (mg kg^{-1}) (nd—not determined)

Water solubility (mg kg^{-1})	Glass	Silicon sealant	Epoxy resin
Calcium	0.00	0.00	0.00
Chloride	8.33	nd	nd
Magnesium	2.43	0.00	0.00
Potassium	2.67	0.00	0.00
Silicon	46.37	0.00	0.00
Sodium	33.00	23.26	0.00
Sulphate	16.67	20.94	92.31
Zinc	0.00	2.33	0.00

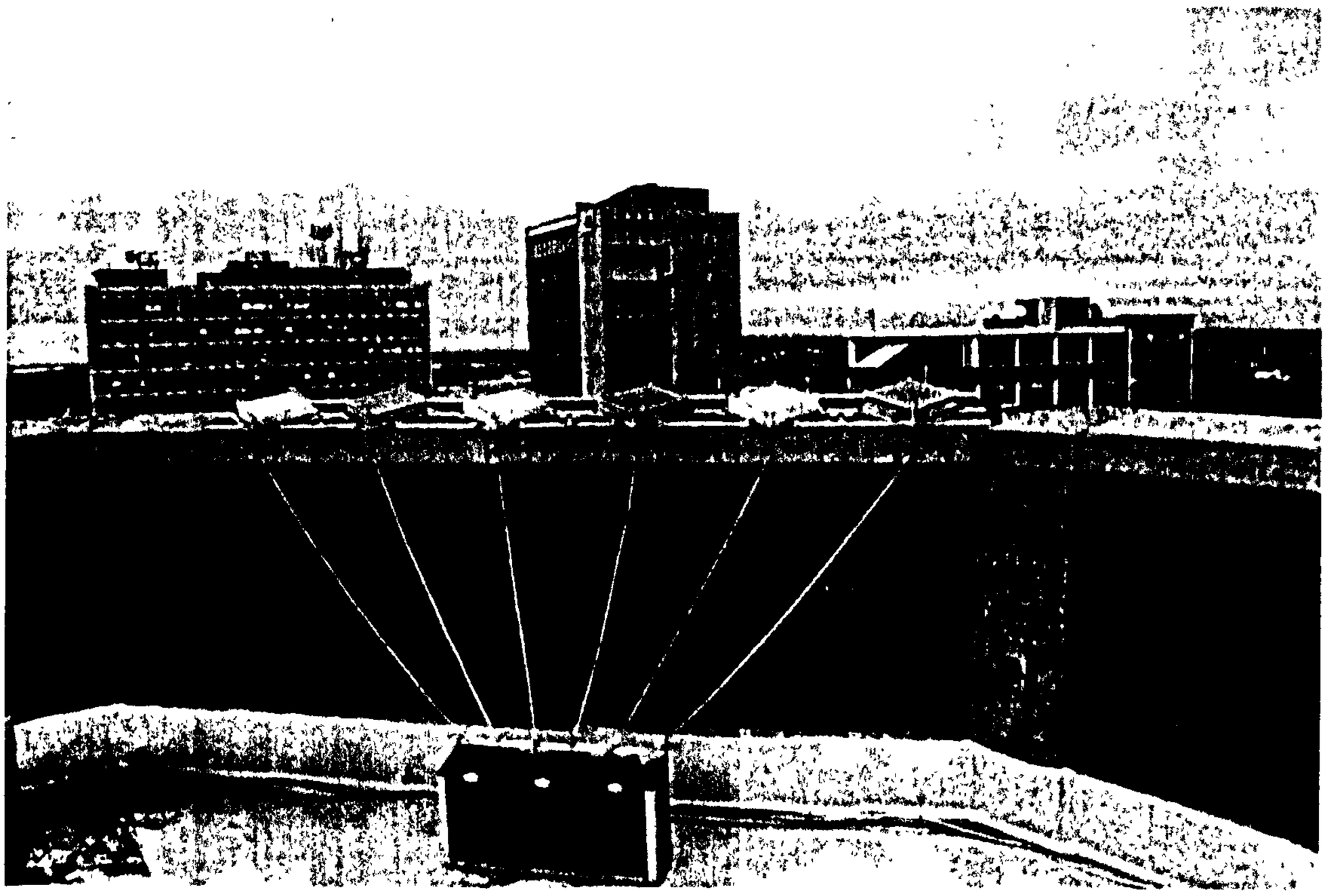

Fig. 2. Sandstone microcatchments at the University of Wolverhampton.

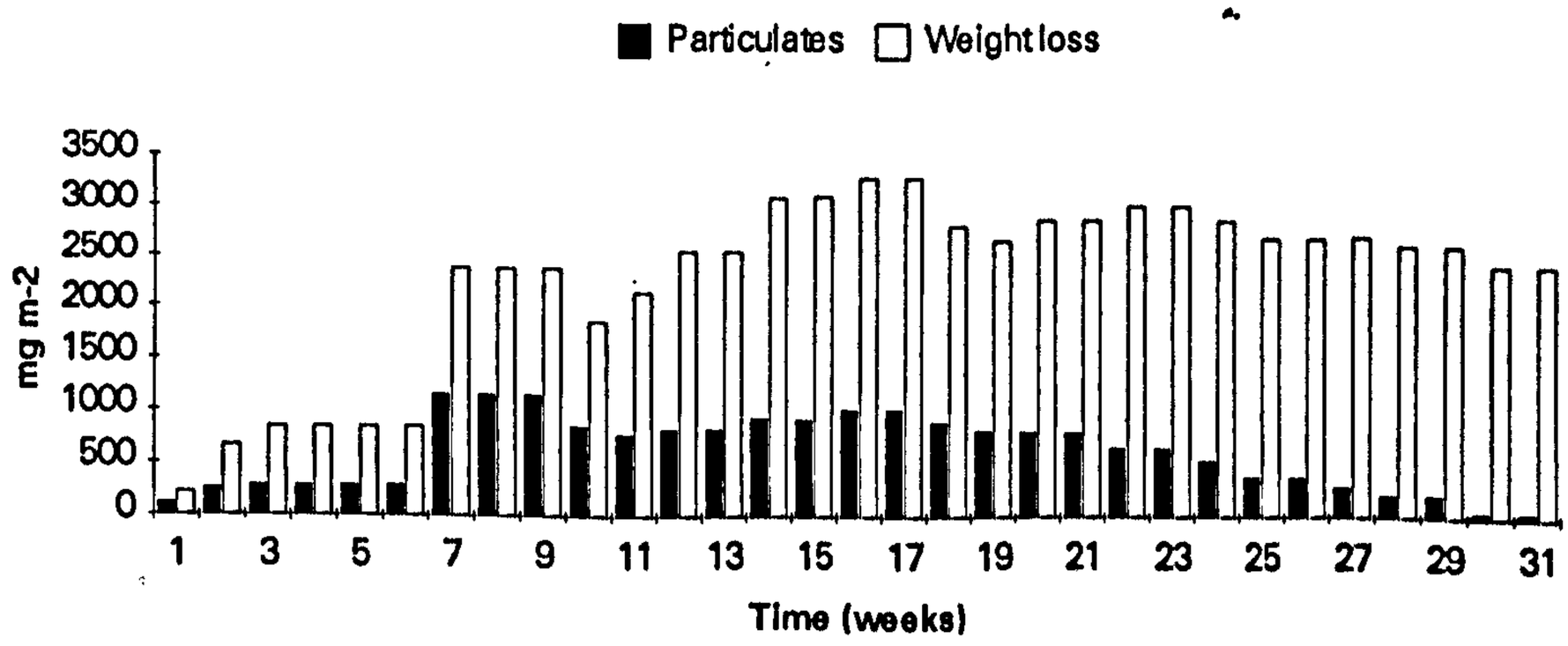

Fig. 3. Cumulative particulate loss and total weight loss (mg m^{-2}).

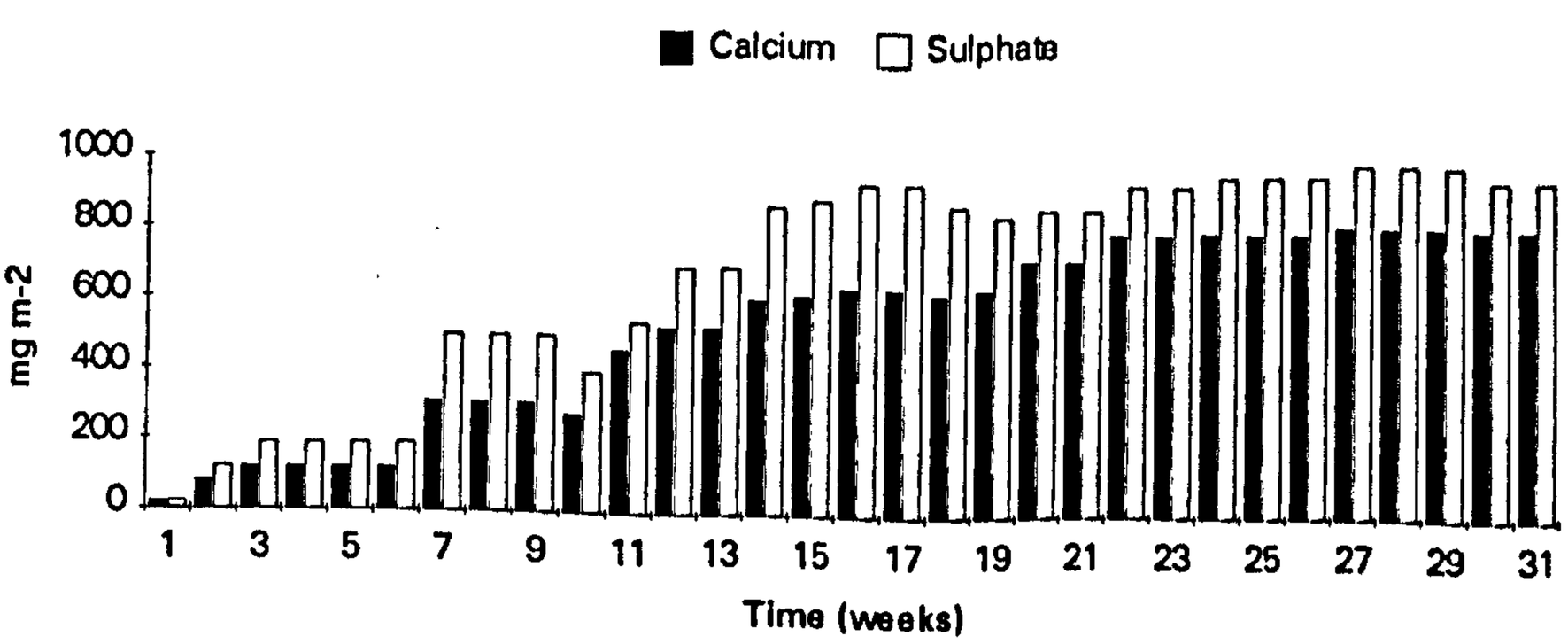

Fig. 4. Cumulative calcium and sulphate loss (mg m^{-2}).

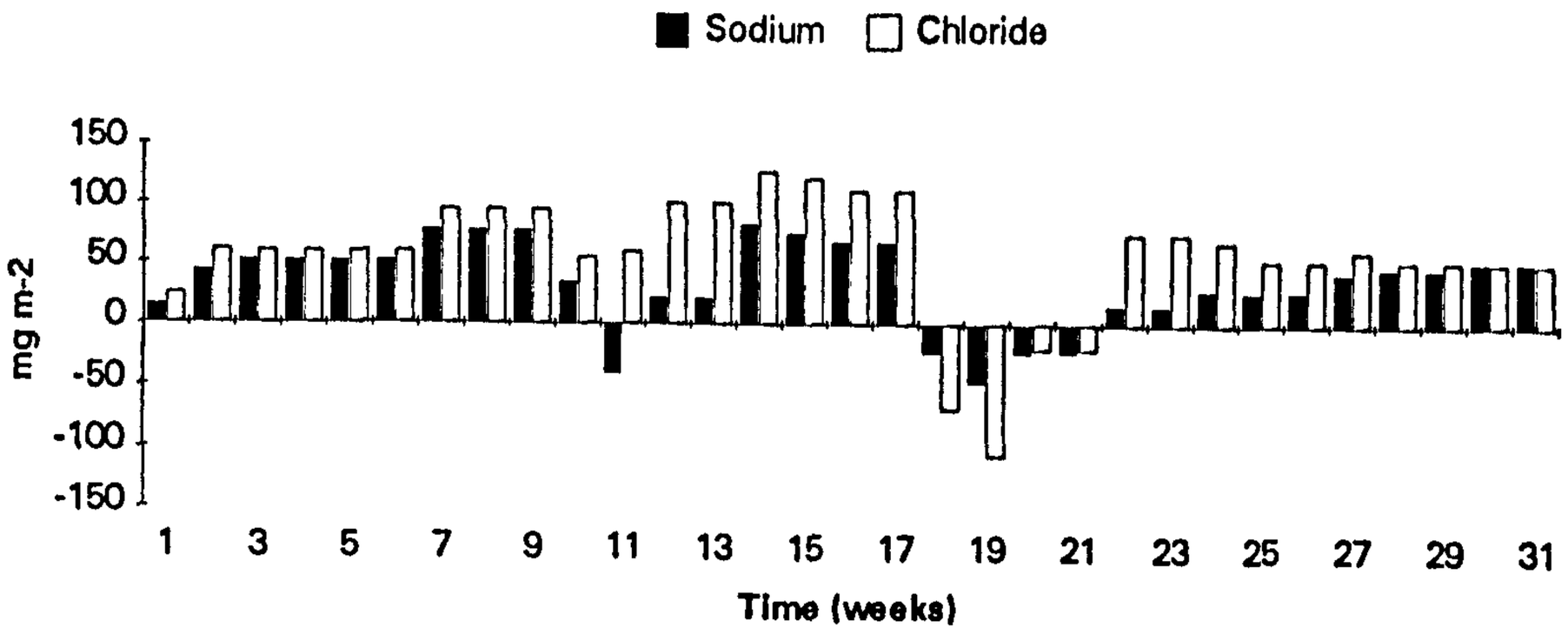

Fig. 5. Cumulative sodium and chloride loss (mg m^{-2}).

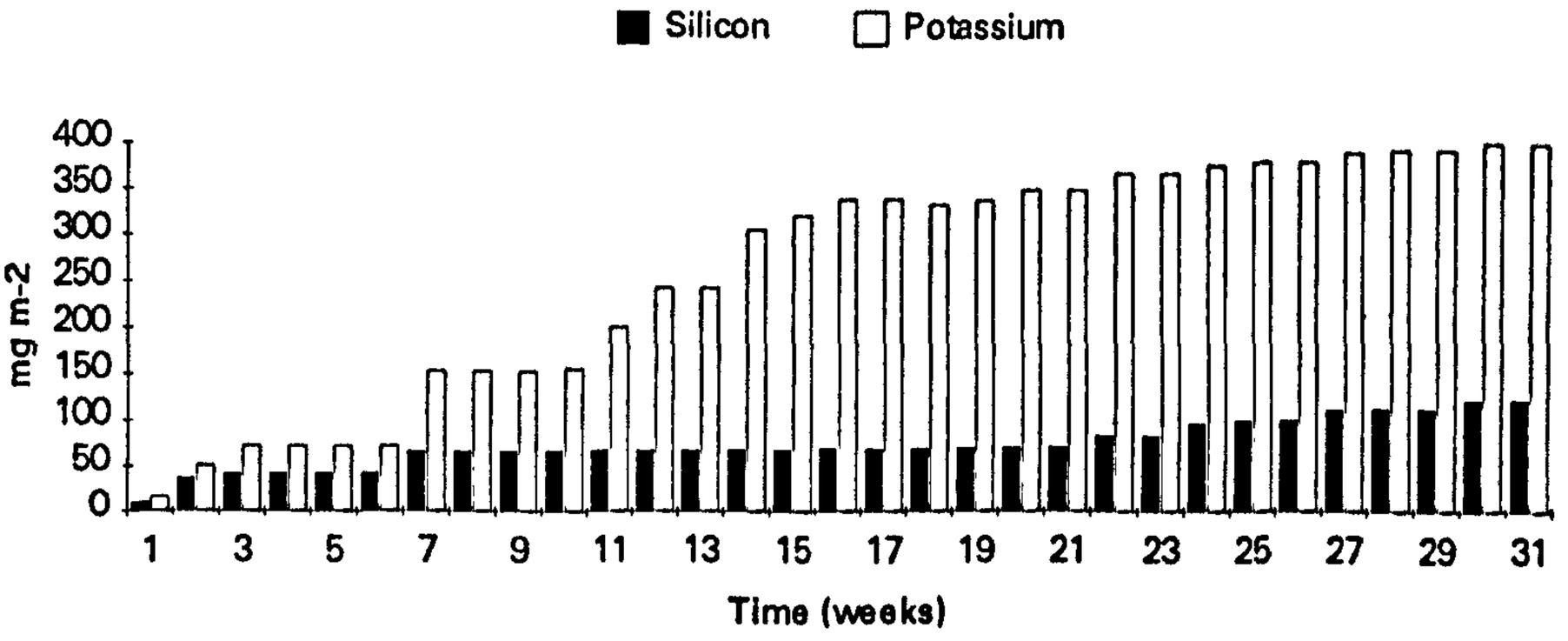

Fig. 6. Cumulative silicon and potassium loss (mg m^{-2}).

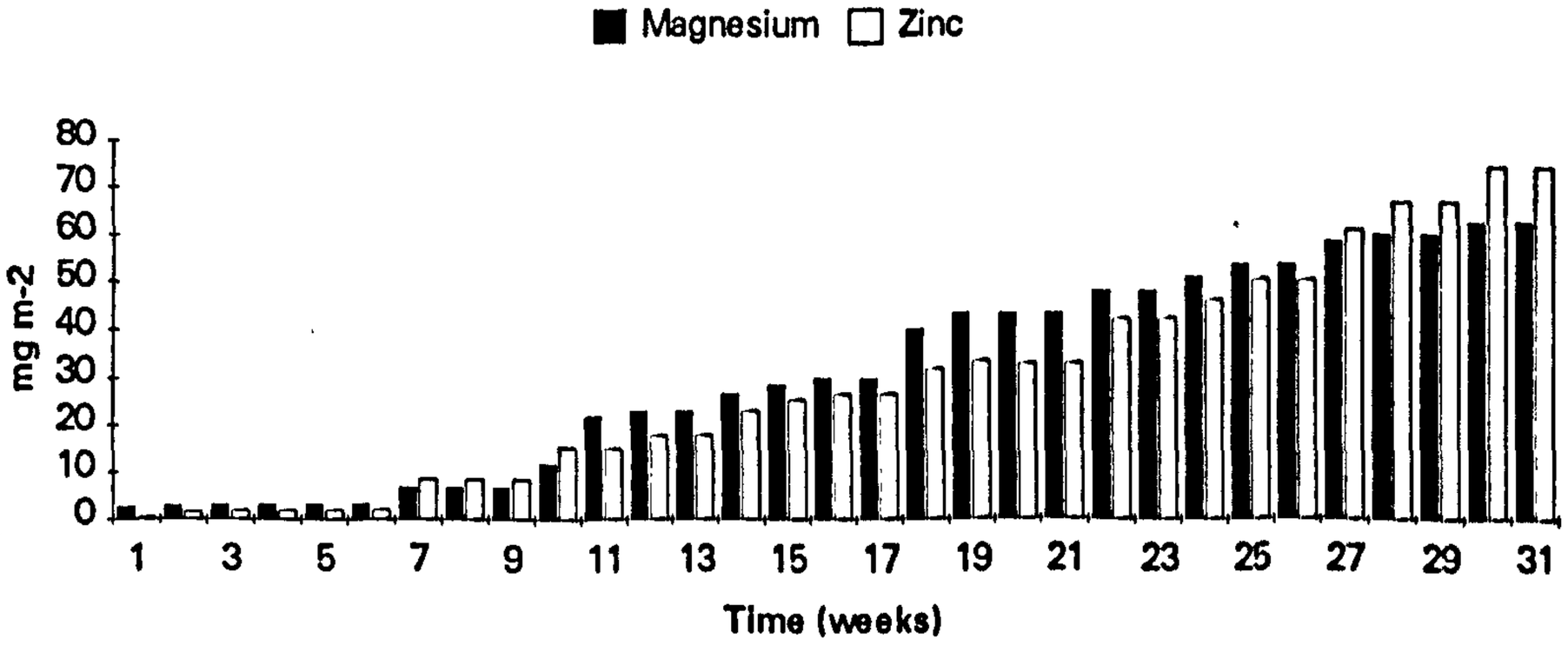

Fig. 7. Cumulative magnesium and zinc gain (mg m^{-2}).

DISCUSSION AND IMPLICATIONS

Physical weathering

On average 55% of the precipitation received by the sandstone is absorbed (Table 3). This is due to the physical properties of the stone, especially porosity. Initially, the dry sandstone absorbs precipitation until either the stone becomes saturated or the rainfall intensity exceeds the infiltration rate. When precipitation ceases the moisture stored in the stone is lost by evaporation at a rate dependent on the current meteorological conditions.

For the first nine weeks of exposure (28.9.93–30.11.93) the loss of particulate matter from Hollington Sandstone was found to be relatively constant, with a mean weekly particulate loss of 128.0 mg m^{-2} $week^{-1}$ (Fig. 3). Analysis of this data using a paired *t*-test shows the difference between the sandstone and control microcatchments to be significant at the $P < 0.05$ level. Linear regression shows this loss to be positively correlated with weekly precipitation volume with a correlation coefficient of 0.991. The most likely explanation for this initial loss is the loosening of sandstone grains in the cutting process, which detach due to raindrop impact. This is supported by analysis of particulate matter trapped on the filter membranes which was found to be rich in silicon, potassium and aluminium. These are the main constituents of the sandstone (Table 1). Since this initial loss there has been an uptake of particulate matter by the sandstone. Again, this was found to be significant at the $P < 0.05$ level. This may be due to the porous nature of the stone, trapping atmospheric particles within its structure. This process may be causing the initial formation of a sand-

Table 3. Mean runoff volumes for sandstone and control microcatchments (ml m^{-2}) and percentage of precipitation absorbed by the sandstone (na—not applicable)

Date	Time (weeks)	Control runoff volume (ml m^{-2})	Sandstone runoff volume (ml m^{-2})	Precipitation absorption (%)
28.09.93	0	na	na	na
05.10.93	1	18,615	3430	82
12.10.93	2	21,259	12,561	61
19.10.93	3	8657	8037	7
26.10.93	4	0	0	na
02.11.93	5	0	0	na
09.11.93	6	4277	0	100
16.11.93	7	60,141	46,816	22
23.11.93	8	0	0	na
30.11.93	9	6797	0	100
07.12.93	10	10,702	3843	64
14.12.93	11	25,247	19,111	24
21.12.93	12	25,061	21,424	15
28.12.93	13	0	0	na
04.01.94	14	44,254	43,386	2
11.01.94	15	13,264	11,590	13
18.01.94	16	13,966	13,491	3
25.01.94	17	10,723	0	100
01.02.94	18	8946	2417	73
08.02.94	19	14,379	3863	73
15.02.94	20	10,082	5372	47
22.02.94	21	1797	0	100
01.03.94	22	15,846	9772	38
08.03.94	23	0	0	na
15.03.94	24	21,424	5847	73
22.03.94	25	0	0	na
29.03.94	26	21,714	7045	68
05.04.94	27	34,585	18,078	48
12.04.94	28	15,681	6467	59
19.04.94	29	0	0	na
26.04.94	30	18,449	3388	82
03.05.94	31	0	0	na
Total	31	425,866	245,938	58
Mean	na	13,739	7933	55

stone crust by blocking the pores in the outer layer of the sandstone. If this is the case, the pores may ultimately become blocked, causing moisture to be trapped behind the crust, which may cause crustal detachment [5].

Formation of soluble salts

The patterns of calcium and sulphate losses are very similar, suggesting that the two elements are combining to form the salt gypsum ($CaSO_4.2H_2O$) or possibly anhydrite ($CaSO_4$)(Fig. 4). Paired *t*-tests show the difference between the sandstone and control microcatchments to be highly significant for both calcium and sulphate. Gypsum is an extremely common salt found in deteriorated stone work and it affects many different types of building stone. Formation of gypsum is often attributed to the sulphation of calcium, contained within the stone or derived from the mortar surrounding the stone, with atmospheric sulphur oxides (SO_x). In the case of Hollington Sandstone the calcium content is extremely low, about 0.06% (expressed as CaO) (Table 1). Although this appears insignificant it provides approximately 40,000 mg of calcium in a metre square slab of Hollington Sandstone. This is sufficient to account for the calcium lost to date, but it is possible that an atmospheric source of calcium is increasing the rate of gypsum formation. This can be explained by the dry deposition of calcium onto the sandstone, due to the absorption of water increasing the time of wetness of the stone, which enhances the adhesion of particulates and the uptake of soluble gasses [11]. Dry deposition of calcium onto an almost pure silicate sandstone has previously been quoted as a mechanism responsible for gypsum formation [12]. However, no data was supplied on the calcium content of the sandstone [12] and this is essential to assess the absolute importance of atmospheric calcium upon gypsum formation.

Once gypsum has formed in the sandstone it remains until the next rainfall event, when it is taken into solution. Where rainfall is great enough to form runoff, the gypsum may be lost. However, when runoff does not occur the gypsum recrystallises as the sandstone dries out. The role of runoff washing gypsum from sandstone is shown by linear correlations between sulphate loss and weekly runoff volume, and calcium loss and weekly runoff volume, with correlation coefficients of 0.846 and 0.705 respectively. If gypsum builds up in the pores of the sandstone it can exert pressure by changes in volume, either due to a change in hydration state or cycles of dissolution and re-crystallisation or differential thermal expansion. Furthermore, it may assist in the blocking of pores in the sandstone. Further analysis of the data for calcium and sulphate gives a molecular ratio of 1.74. This indicates calcium may also be lost from the stone by another mechanism. Previous research on sandstones containing cal-

cium carbonate found this extra calcium to be lost due to the direct dissolution of calcium carbonate [12]. Calcium carbonate occurs as a cementing agent in sandstones and its dissolution may in time cause weakening in the areas of stone it is dissolved from.

Halite (NaCl) also appears to be forming in the sandstone (Fig. 5). Both sodium and chloride show an irregular, but similar pattern of losses and gains. The presence of halite is supported by a mean sodium to chloride molecular ratio of 1.02. The exact mechanism of halite formation is not clear, but it may be derived from marine aerosols [1]. Paired *t*-tests show the difference between the sandstone and the glass microcatchments is not significant for sodium, but it is significant for chloride at the $P < 0.05$ level. Although halite exerts almost twice the crystallisation pressure of gypsum it is probably less harmful to the sandstone as it does not undergo transitions between hydration states and it is present in much smaller quantities.

Tests for nitrate salts have shown no consistent trend over the study period and they were only detected in very small quantities. This suggests that nitrates have little direct influence upon the weathering of Hollington Sandstone. Arsenic, aluminium, phosphorous, vanadium, lead, iron, and strontium were also examined, but were present in concentrations below the limits of detection of the analytical techniques used.

Formation of clays

The formation of clays at the earth surface is generally a result of the breakdown of unstable silicate minerals [13]. Hollington Sandstone contains approximately 3% orthoclase ($KAlSi_3O_8$) which is a common clay forming mineral. This weathers by the process of acidic hydrolysis to leave a clay deposit, usually *kaolinite* [$Al_4Si_4O_{10}(OH)_8$] [equation (2)].

$$4KAlSi_3O_8 + 8H^+ = Al_4Si_4O_{10}(OH)_8 + 4K^+ + 8Si^+ + 14O^{2-}$$

orthoclase + hydrogen ions from water = kaolinite + potassium ions + silicon ions + oxygen ions. (2)

Evidence for the hydrolysis of orthoclase contained in the sandstone is provided by the loss of potassium (Fig. 6). The process of hydrolysis is dependent on water to supply hydrogen ions and this is demonstrated by a linear correlation between potassium loss and weekly runoff volume with a correlation coefficient of 0.909. Equation (2) also shows a silicon loss and this has been found for the sandstone microcatchments (Fig. 6). Both potassium and silicon losses are statistically significant at the $P < 0.05$ level.

Kaolinite does not cause disruptive pressure in the sandstone as it is a non-swelling clay (i.e. the volume does not change with the uptake of water). However, the formation of kaolinite causes a reduction in the compressive strength of the sandstone by approximately 10 MPa for every 1% increase in kaolinite [14]. Furthermore, the porosity of the sandstone increases due to increasing kaolinite [14]. This may increase the stone's susceptibility to physical stresses and previous research gives some evidence for a general reduction in durability with increased kaolinite content [14].

Small quantities of magnesium and zinc were found to build up in the sandstone to give a cumulative enrichment (Fig. 7). Zinc enrichment in soiled sandstone, due to atmospheric pollution, has been reported previously [3]. In this research the only source of zinc is atmospheric, but the gain of zinc is not statistically significant. Magnesium gain is significant at the $P < 0.05$ level and is correlated with weekly precipitation volume with a correlation coefficient of only 0.132. This low coefficient suggests that magnesium does not come from wet deposition, and therefore it is most likely derived from dry deposition. For magnesium to be accumulating in the sandstone it must form compounds in the stone that are not dissolved in the runoff. It is most probable that magnesium cations are binding to clays contained in the sandstone. If this is the case, magnesium is not influencing the weathering of the stone greatly.

Biodeterioration

Although no accurate assessment has been made of the biological colonisation of the microcatchments, it was apparent that after 16 weeks of exposure green algae were present on the sandstone, but not on the glass microcatchments. This was identified by a greening on the filter membranes used in sample preparation and this has intensified with time. If fresh algae are sufficiently dense they give the stone a slimy green appearance. However, when they die they turn black and may remain trapped in the stones pores, thus contributing to the formation of a blackened crust. Furthermore, algae may increase the water retention in the stone and this may in turn increase chemical weathering (e.g. kaolinite formation).

SUMMARY AND CONCLUSIONS

Hollington Sandstone is a high quality building stone which passes the acid immersion test and endures the salt crystallisation test well [15]. At present these are the conventional tests employed to evaluate building stone durability. This study shows that the weight loss experienced by the stone in 31 weeks is approximately one eighth of that experienced by Portland Limestone in Dublin for the same duration [9]. This may be somewhat misleading as the dominant deterioration mechanism affecting Hollington Sandstone is the formation and detachment of surface crusts, as compared to dissolution for Portland Limestone. Therefore, weight loss estimates are of limited use for Hollington Sandstone. Of more use is the identification of possible mechanisms that could be involved in sandstone crust formation.

Results highlight that crusts may form on Hollington Sandstone due to the blocking of pores by atmospheric particulates and algae. The filter membranes used in the sample preparation are currently undergoing fully quantitative elemental analysis in order to gain an insight into the nature of these particulates. Additionally, pores may be blocked by salts, especially gypsum and possibly halite. It seems likely that both of these processes occur concurrently and probably complement each other, with gypsum crystals growing around particulates and algae, hence trapping them within the sandstones pores [1].

Gypsum accumulation is seen to take place from calcium contained within the sandstone and, in this study, no conclusive evidence exists for the atmospheric deposition of calcium.

The results suggest that crust detachment may be aided by gypsum and possibly halite exerting underlying pressures due to changes in temperature and moistue availability in the pores of the stone. Detachment could also be aided by a weakening of the sandstone below the crust, due to the loss of calcium carbonate cement. Further weakening could be caused by the weathering of orthoclase to form kaolinite. Based on the assumptions that potassium loss is a good indicator of the rate of kaolinite formation and that this formation is linear over time, and that the estimate of a reduction in compressive strength of 10 MPa for every 1% increase in kaolinite is valid [14], it can be estimated that, in this study, kaolinite formation will reduce the strength of Hollington Sandstone by 1 MPa in around 45 years. This figure is not precise and only provides an indication as to the role orthoclase hydrolysis may have in sandstone deterioration. As the sandstone has a compressive strength of around 35 MPa significant weakening will take considerable time. However, the trapping of moisture behind the crust may increase the rate of kaolinite formation in this zone, which could aid crustal detachment.

The chemical and mineralogical composition of a sandstone are shown to be of significant use in evaluating sandstone deterioration and this information may assist architects and others involved in the selection of sandstones for building purposes. The microcatchment technique is shown to be a successful method for gaining information on stone deterioration and, although time consuming, it is suitable for comparing the durability of different stones as well as conservation treatments.

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REFERENCES

1. B. Smith, R. Magee and W. Whalley, Breakdown patterns of quartz sandstone in a polluted urban environment: Belfast, N. Ireland, in *Rock Weathering and Landform Evolution* (Edited by D. Robinson and R. Williams), pp. 131–150, John Wiley, Chichester (1994).
2. P. Malesani and S. Vannucci, Decay of Pietra Serena and Pietraforte, Florentine building stones: petrographic observations. *Studies in Conservation* 19, 36–50 (1974).
3. C. Sabbioni and G. Zappia, Decay of sandstone in urban areas correlated with atmospheric aerosol. *Water, Air and Soil Pollution* 63, 305–316 (1992).
4. K. Bos and F. Gullentops, Ijzerzandsteen als bouwsteen in en rond het Hageland. *Bulletin Belgique Ver. vr. Geologie* 99, 131–151 (1990).
5. B. Bluck and J. Porter, Sandstone buildings and cleaning problems. *Stone Industries* 26(2), 21–27 (1991).
6. B. Smith and J. Mcgreevy, Contour scaling of a sandstone by salt weathering under simulated hot desert conditions. *Earth Surface Processes and Landforms* 13, 697–705 (1988).
7. E. Wendler, D. Klemm and R. Snethlage, Contour scaling on building facades—dependence on stone type and environmental conditions, in *Analytical Methodolgies for the Investigation of Damaged Stones*, pp. 1–7, Pavia, 14–21 September (1990).
8. D. Jeffrey, T. Cooper, P. O'Brien, J. Lewis, D. Slattery and G. O'Daly, A test-rig for determining short term weathering rates of building materials under urban environmental conditions, in *The Effects of Air Pollution on Historic Buildings and Monuments*, pp. 83–95, Padua, 30 September–2 October (1985).
9. T. Cooper, P. O'Brien and D. Jeffrey, Rates of deterioration of Portland Limestone in an urban environment. *Studies in Conservation* 37, 228–238 (1992).
10. D. Hunt and A. Wilson, *The Chemical Analysis of Water*, 2nd edition, Royal Society of Chemistry, London (1986).
11. G. Amoroso and V. Fassina, *Stone Decay and Conservation: Material Science Monographs* 11, Elsevier, Amsterdam (1983).
12. M. Steiger, F, Wolf and W. Dannecker, Deposition and enrichment of atmospheric pollutants on building stones as determined by field exposure experiments, in *Conservation of Stone and Other Material* (Edited by J. Thiel), Volume 1, pp. 35–42, E. & F. N. Spon, London (1993).
13. B. Velde, *Introduction to Clay Minerals*, Chapman & Hall, London (1992).
14. J. Sramek, Kaolinitic quartz sandstones—the influence of mineralogy on physical–mechanical properties and durability, in *7th International Congress on Deterioration and Conservation of Stone* (Edited by J. Rodrigues, F. Henriques and F. Jeramias), Volume 1, pp. 67–77, Lisbon, 15–18 June (1992).
15. E. Leary, *The Building Sandstones of the British Isles*, HMSO, London (1986).

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THE EFFECTS OF ATMOSPHERIC POLLUTANTS UPON SANDSTONE: EVIDENCE FROM REAL TIME MEASUREMENTS AND ANALYSIS OF DECAY FEATURES ON HISTORIC BUILDINGS.

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INTRODUCTION

Due to the urbanisation and industrialisation of the West Midlands, UK, historic sandstone buildings are exposed to atmospheric pollution. In order to assess the impact of this pollution upon their deterioration, chemical analysis of runoff water, from sandstone and control surfaces, has been carried out. The amount of stone affected by atmospheric pollution has been quantified by surveying selected sandstone buildings.

METHODS

Six microcatchments (1), were used to measure the weathering of sandstone over one year. Three were fitted with 50 mm thick slabs of Mottled Hollington Sandstone, a medium grained ferruginous Triassic Sandstone widely used in Central England. As a control, three microcatchments were fitted with rough textured glass plates. The microcatchments were installed at the University Urban Meteorological Station, Wolverhampton. They were orientated to the South West at a 15 degree angle to the horizontal, with the outlet tube at the lowest point. Each tube fed into individual polyethylene bottles housed in an insulated box. Rainfall runoff from the microcatchments was collected weekly, the volume and pH measured, and the samples filtered through Whatman Cellulose Nitrate membranes (0.45µm pore size). Filtrates were analysed for chloride, sulphate and nitrate, using Ion Chromatography, and calcium and sodium using Inductively Coupled Plasma Spectrometry. Filters were dried and quantitative elemental analysis carried out using X-Ray Fluorescence Spectrometry. To assess changes in the sandstone, results were averaged for control and sandstone microcatchments, and cumulatively totalled. The control were subtracted from the sandstone values to give cumulative losses (mg m^{-2}) for each particulate and chemical species. Paired t-tests evaluated differences between the sandstone and control.

The building survey was carried out in a 700 km^2 area, centred on the West Midlands (NGR SP 010890). Churches were chosen for the comparative survey as they are easily located, tend to be free standing and, in the West Midlands, many were built of ferruginous sandstone in the 19th century. Cleaned or heavily restored buildings were excluded, leaving twenty four 19th century churches. Six 12th century churches were also included in order to gain a more even distribution in the survey area. Three forms of weathering considered relevant to atmospheric pollution were examined (Table 1). Blackened stone is generally considered to be caused by the deposition of atmospheric particulates, although in some cases algae may cause a similar effect (2). If this was apparent, then it was noted as a different weathering form. For each

wall of the building the basic environmental conditions were recorded. The weathering was assessed by examining 1 m^2 quadrats of sandstone at heights of 0.2-1.2 m and 1.2-2.2 m every 2 m along the wall. For each observation, the percentage of cover of the weathering forms were recorded to the nearest five per cent. Effects of wall orientation on the occurrence of the weathering forms were examined by Analysis of Variance.

Table 1. Classification of weathering forms related to atmospheric deposition.

Weathering Type	Description
Black Soiling	Black coating on the sandstone surface.
Black Flaking	Detaching black surface layer (thickness of detaching stone < 3mm).
Black Scaling	Detaching black surface layer (thickness of detaching stone > 3mm).

To evaluate the physical effects of black soiling, water absorption rates were measured on stone that has been exposed to an inner city environment (Birmingham, UK) since about 1860. Half of the stone was left with its black soiling, whilst the other half was cleaned by sandblasting. Water absorption was measured on both halves with Karsten Tubes (3). Paired t-tests evaluated the difference between the two halves.

RESULTS

For the first nine weeks of exposure particulate matter was lost from the stone (Fig. 1) (i.e. losses from the sandstone were significantly ($P<0.05$) greater than from the control). Particles had high concentrations of silicon, potassium and aluminium (the main constituents of the stone). After this initial loss, there was uptake of particulate matter (Fig. 1) ($P<0.05$), rich in silicon, aluminium and iron (Table 2).

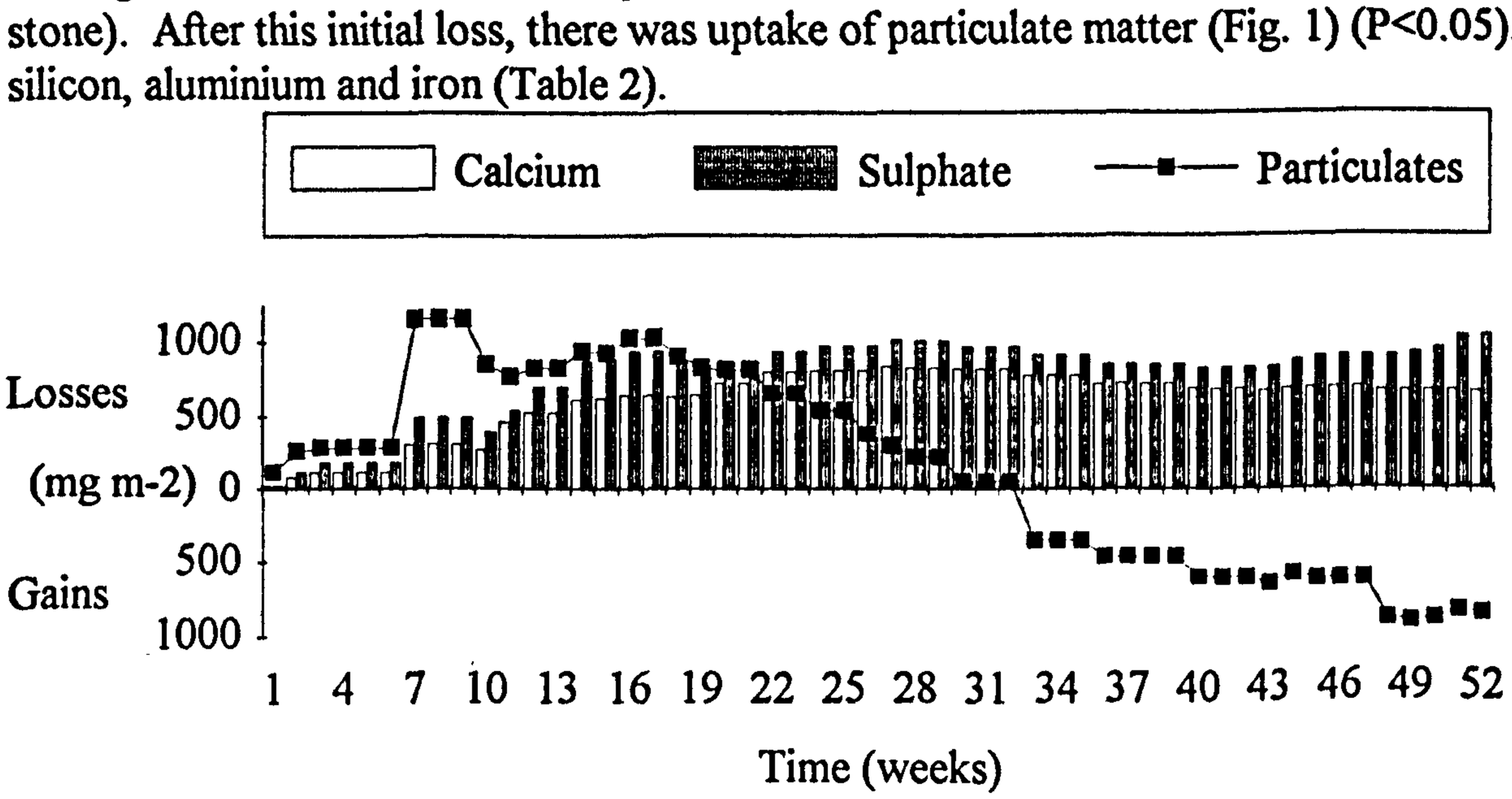

Figure 1. Cumulative changes in calcium, sulphate and particulate matter.

Table 2. Cumulative gains as particulate matter (weeks 10-52).

($mg\ m^{-2}$)	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	Si_2O	ZnO	Total (4)
Total gain	508.5	62.3	155.0	18.5	69.5	26.5	2005.8	5.0	2851.1
Mean weekly gain	11.8	1.4	3.6	0.4	1.6	0.6	46.6	0.1	66.3
Maximum weekly gain	62.6	8.6	21.5	5.8	9.1	9.1	252.9	0.6	357.9
Minimum weekly gain	-32.8	-2.9	-22.3	-9.9	-2.8	-2.3	-198.8	-0.8	-255.9
Standard deviation	20.0	2.3	7.2	2.8	2.2	1.8	77.9	0.2	110.2

Soluble calcium and sulphate losses were significantly ($P<0.01$) greater from the sandstone than the control. The pattern of losses were similar suggesting calcium and sulphate were combining to form the salt gypsum ($CaSO_4.2H_2O$) or possibly anhydrite ($CaSO_4$) (Fig. 1). Small quantities of halite (NaCl) also formed. Nitrates showed no consistent trend over the study period and were only detected in very small quantities.

Deterioration related to atmospheric deposition was present in 86% of the quadrats and on average accounted for 33% of the total deterioration found. Orientation influenced the occurrence of blackened stone and relevant deterioration forms, with the greatest quantities on south and west facing walls (Fig. 2). Orientation has a significant affect upon black flaking ($P<0.05$), scaling ($P<0.01$) and soiling ($P<0.01$).

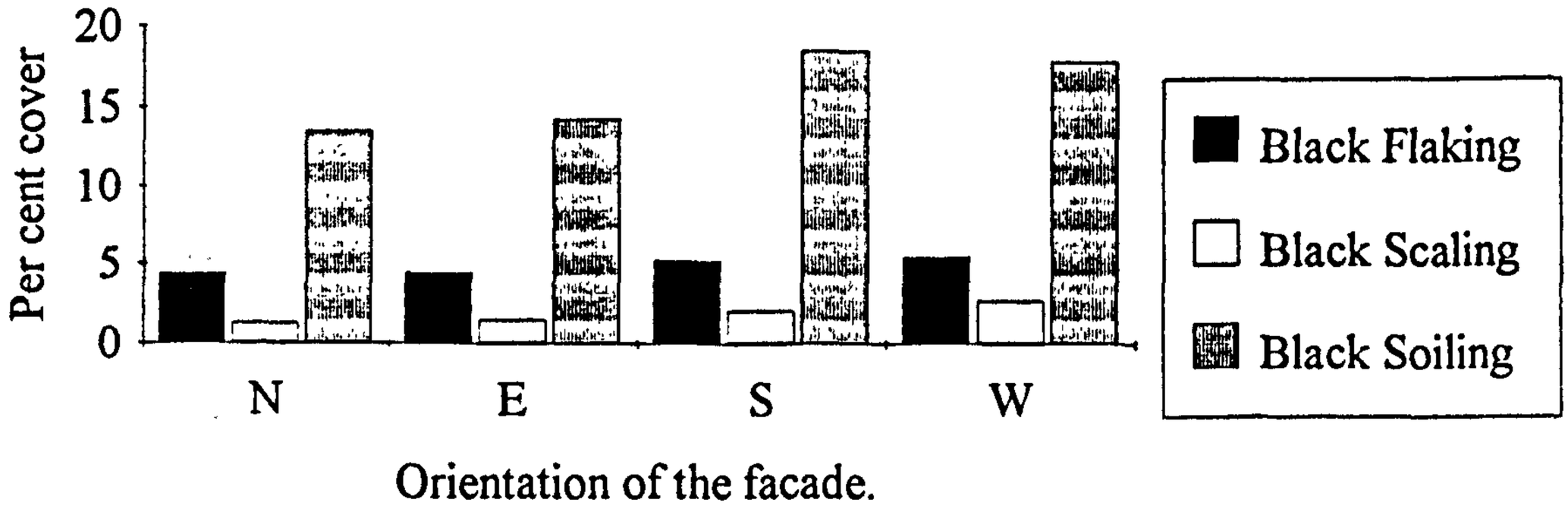

Figure 2. Occurrence of black flaking, scaling and soiling.

Water absorption measurements show blackened and clean stone absorb water at the mean rate of 0.07 l $m^{-2}hr^{-1}$ and 0.68 l $m^{-2}hr^{-1}$ respectively. Black soiling has a significant ($P<0.01$) affect upon water absorption.

DISCUSSION

The initial loss of particulate matter was probably due to the detachment of sandstone grains by raindrop impact, which were first loosened when the stone was cut. The later uptake of particulates was most likely due to the porous nature of the stone, trapping atmospheric particles within its structure. The chemistry of this particulate matter (Table 2) is typical of spherical particles formed by fossil fuel combustion (5). This process may cause the initial formation of black soiled sandstone (2). The sandstone pores may ultimately become blocked, trapping moisture behind the crust, which may result in black flaking and scaling (2). This is supported by water absorption measurements, which suggest that black soiling can reduce water absorption rates by a magnitude of ten.

Gypsum is commonly found in many types of deteriorated stone. Its formation is generally attributed to the sulphation of calcium with atmospheric sulphur oxides. Calcium may be contained within the stone, derived from the mortar surrounding the stone or from dry deposition (6). The calcium content of Hollington Sandstone is extremely low, about 0.06% (as CaO), and therefore provides approximately 40,000 mg m^{-2} of calcium. This is sufficient to account for the calcium lost. However, particulate calcium (Table 2) may also be involved in gypsum formation (5). Gypsum can exert pressure in the pores of the stone by changes in volume, either due to a change in hydration state, cycles of dissolution and re-crystallisation or differential thermal expansion. Gypsum can also assist in the blocking of pores, with gypsum

crystals growing around particulate matter and therefore trapping it (6). Furthermore, gypsum may cause the loss of calcium carbonate, which occurs as a natural cementing agent in sandstone. Unlike gypsum, halite does not show consistent trends and is present in smaller quantities. It exerts almost twice the crystallisation pressure of gypsum, but is probably less harmful, as it does not undergo transitions between hydration states and is less abundant.

The formation of black soiling, scaling and flaking can be explained by the processes outlined above. The occurrence of weathering forms depends on the degree of exposure, as this influences the magnitude of the processes and the depth at which they occur. The preference of black weathering forms for south and west facing walls may be related to the fact that these facades are exposed to prevailing winds. This increases the inputs of wind-driven rain and hence wet deposition and adhesion of particulate matter. It is unclear if the prevailing wind alone can increase dry deposition, as this is greatly influenced by local wind turbulence (3). The processes which aid the detachment of black scales and flakes are caused by cycles of wetting and drying, and heating and cooling. Due to the prevailing wind direction and the incidence of solar radiation, the greatest number of cycles will generally occur on the south and west facades and this may account for the greater occurrence of black scaling and flaking on these walls.

This research shows that deposition of atmospheric sulphur oxides and particulates can explain the formation of decay features, which account for a third of the total sandstone decay found. This highlights the importance of atmospheric pollution upon the deterioration and conservation of historic buildings. Further research is continuing on all forms of sandstone deterioration and the importance of atmospheric pollution will continue to be assessed.

ACKNOWLEDGEMENTS

This work was funded by the Engineering and Physical Sciences Research Council, UK. The technical staff at the University of Wolverhampton were invaluable. J. Oldham Quarries Ltd., Staffordshire, UK, kindly provided the test material. We are grateful to the architects and officials responsible for the buildings used and to S. Padfield for help with surveying.

REFERENCES

1. Halsey, D., Dews, S., Mitchell, D. and Harris, F. 1995. Real Time Measurements of Sandstone Deterioration: A Microcatchment Study, *Building and Environment* (in press).
2. Bluck, B. and Porter, J. 1991. Sandstone buildings and cleaning problems, *Stone Industries*, 26(2): 21-27.
3. Verhoef, L. 1988. *Soiling and cleaning of building facades*, Chapman & Hall, London.
4. The particulate gain, for weeks 10 to 52, shown in Table 2 (2851 mg m^{-2}) is greater than that of Fig. 1 (2007 mg m^{-2}). The stone was colonised by algae, which were consistently lost as particulate material, offsetting the real weight gains to give the data for Fig. 1. Table 2 shows more realistic weight gains as the effects of algae on the weight changes are not shown by X-Ray Fluorescence Spectrometry as it does not detect organic matter.
5. Fassina, V. 1992. The stone decay of the Portal of the Basilica of SS. Giovanni E Paolo in Venice. In: Rodrigues, J., Henriques, F. and Jeremias, F. (eds.) *7th International Congress on the Deterioration and Conservation of Stone*. Lisbon, Portugal, 15-18.6.92, pp. 119-128.
6. Smith, B., Magee, R. and Whalley, W. 1993. Breakdown patterns of quartz sandstone in a polluted urban environment, Belfast, Northern Ireland. In: Robinson, D. and Williams, R. (eds.) *Rock weathering and landform evolution*, J. Wiley & Son, Chichester, pp. 131-150.

5 The black soiling of sandstone buildings in the West Midlands, England: regional variations and decay mechanisms

D.P. HALSEY, S.J. DEWS,
D.J. MITCHELL and F.C. HARRIS

ABSTRACT

The distribution of sandstone weathering forms has been examined for churches built of ferruginous sandstone in the West Midlands, England. The surveyed buildings had not been heavily restored or cleaned; and the majority were built in the nineteenth century of Quartz Arenites. The survey recorded percentage cover of each weathering form in 1 m^2 quadrats for thirty buildings situated in two 40 km by 10 km transects across the West Midlands. One transect ran from north to south and the other from east to west. Around 1400 quadrats were completed and regional weathering patterns were examined using cluster analysis and contour mapping. The transects show that black soiling covers < 10% of sandstone façades in rural areas to the west of the conurbation, > 40% of stone in the centre of the conurbation and < 20% in rural areas to the east. Façades in southern areas of the conurbation typically have < 20% black soiling, whereas façades in the north have > 40%. An increase in black soiling caused by urbanisation is clearly demonstrated and there is some evidence that the location of industry may have increased black soiling in certain areas of the conurbation. Coal has historically been the dominant industrial and residential fuel of the West Midlands and Scanning Electron Microscopy shows that coal flyash is prevalent on black soiled sandstone in this area.

INTRODUCTION

The application of sensitive measurement techniques, over short periods of time, is essential to improve our understanding of stone weathering mecha-

Processes of Urban Stone Decay. Edited by B.J. Smith and P.A. Warke.

nisms. However, to evaluate and explain the occurrence of various forms of weathering it is necessary to carry out objective assessments of weathering features that have formed over significant time periods. Stone buildings, of a known age, provide a means to carry out these assessments, but much of the research on the weathering of buildings is in the form of case studies, involving single or small numbers of buildings. This investigation reports some of the findings from a survey of weathering forms affecting 30 sandstone buildings and relates these findings to various sandstone decay mechanisms.

METHODOLOGY

To achieve a distribution of comparable buildings across rural and urban environments two transects, 40 km long and 10 km wide, were drawn on a map of the West Midlands. A north–south and an east–west transect, centred on the West Midlands conurbation (NGR SP 010890), crossing both rural and urban areas, were selected. An initial examination of buildings along these transects revealed that most sandstone buildings were churches. Therefore, it was decided that the survey should concentrate on churches, which are generally free standing in graveyards and orientated according to the cardinal points. Examination of churches in or very close to these transects provided 30 suitable buildings, which showed no evidence of cleaning or major restoration. All were constructed from ferruginous sandstone, typically quartz arenites (presumably quarried from local Permo-Triassic Sandstone formations). Twenty-four of the churches were built in the nineteenth century, while the remaining six were older.

To record the type and amount of weathering, a system to classify the different weathering forms was devised. An existing classification with over 40 different types of weathering, was considered and reduced to 18 forms of sandstone weathering by removing those inappropriate to sandstone and generalising the less common forms of deterioration. This study investigates the findings of three of these forms (black soiling, black flaking and black scaling), but will also refer to total blackened stone, which is the sum of these three forms (Table 5.1). For each building the amount of stone affected by each weathering form was recorded as percentage cover to the nearest 5%. This was done by analysing one metre quadrats of sandstone, between the heights of 0.2 and 1.2 metres, and 1.2 and 2.2 metres, at two metre intervals along the wall. These heights were selected so that the lower one represented stone influenced by the capillary rise of ground water, while the upper one was less influenced. The quadrat interval of two metres was found to be sufficient to account for the spatial variability on most walls. The survey concentrated on vertical walls, but the weathering of horizontal or sloped surfaces, if present, were recorded separately and are not considered in this investigation. Four of the buildings were re-surveyed to check the repeatability of the technique, and t-tests showed no statistically significant difference between original results and those from the repeated survey.

Weathering forms	Description
Black flaking	Detaching black surface layer (thickness of detaching stone < 3mm).
Black scaling	Detaching black surface layer (thickness of detaching stone > 3mm).
Black soiling	Black coating on the sandstone surface.
Total blackened stone	Sum of black soiling, black flaking and black scaling (not a true weathering form).

Table 5.1 Definitions of sandstone weathering forms used in the study.

RESULTS

Data from approximately 1400 quadrats were collected and spatial distributions were analysed using cluster analysis. For each building the average percentage cover, per metre squared, for each of the three weathering forms was collated into a data set and analysed with hierarchical clustering methods. Three conceptually different methods (unweighted arithmetic averaging technique, single linkage method and Ward's method) were used to identify the structure of the data and the number of clusters. All three methods produced similar results, exemplified by the dendrogram produced by the unweighted arithmetic averaging technique (Figure 5.1). Three distinct clusters in the data can be identified. A K-means cluster analysis was carried out to check the composition of the three clusters and provide descriptive statistics and analysis of variance (ANOVA) for the final clusters (Table 5.2). Members of cluster 1 have on average 47% total blackened stone, cluster 2 members 25% and cluster 3 members 11%. ANOVA shows the difference between the means of the three clusters to be statistically significant for all three weathering forms (Table 5.2), giving evidence that the amount of black flaking, scaling and soiling does vary between clusters of buildings. However, a post-hoc comparison of means, Tukey Honest significant difference test for unequal sample sizes, (Table 5.3) shows which cluster means are particularly different from each other. It is apparent that there is strong evidence for a difference in means for black soiling and total blackened stone for each cluster, but the evidence for black flaking and black scaling is not so strong.

To evaluate spatial distributions, building location and cluster membership were plotted onto the survey base map (Figure 5.2). Buildings in

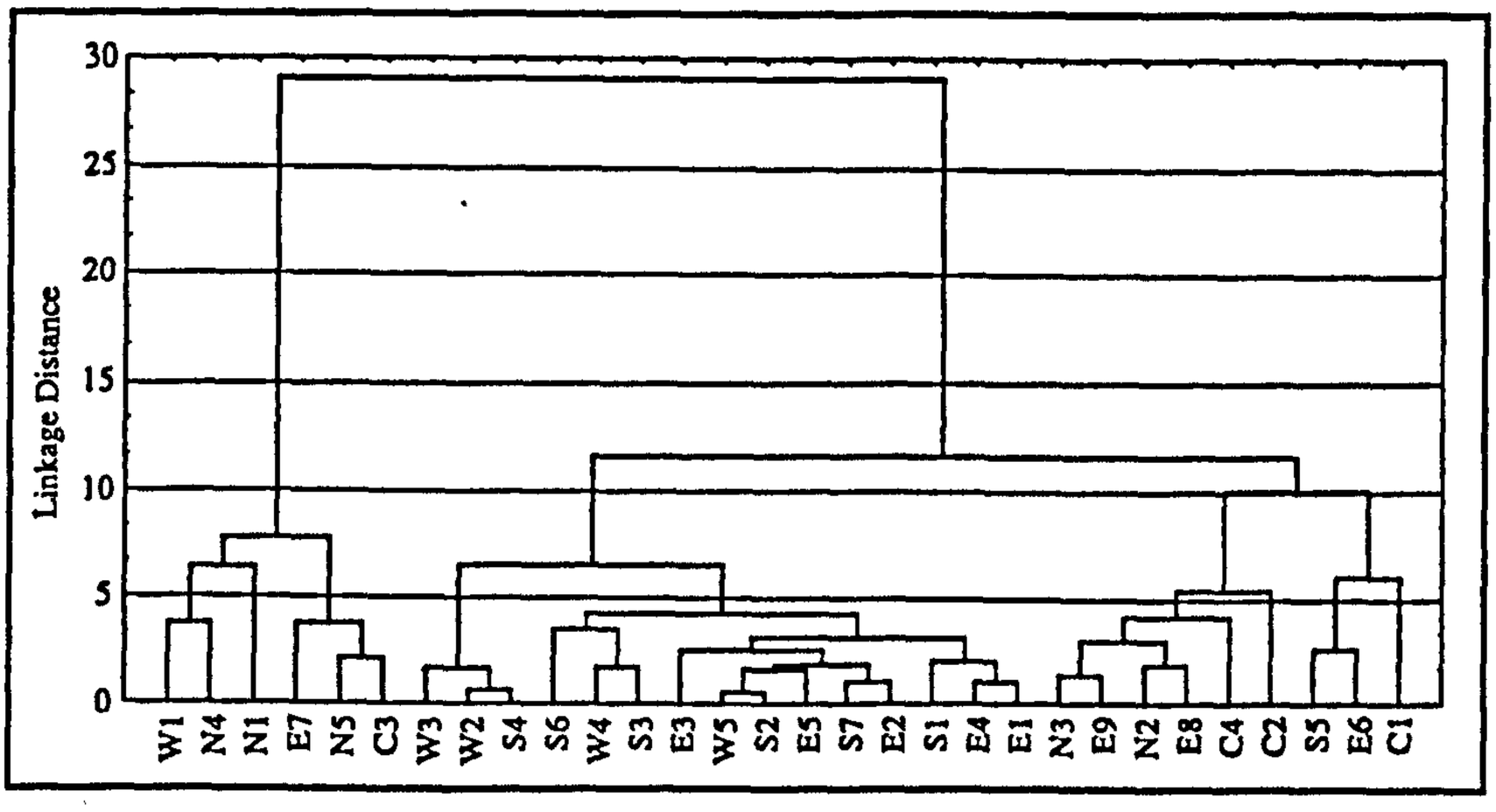

Figure 5.1 Dendrogram produced by unweighted pair-group average technique, using Euclidean distance.

	Cluster 1		Cluster 2		Cluster 3		ANOVA
Weathering forms	Mean cover	Standard deviation	Mean cover	Standard deviation	Mean cover	Standard deviation	p value
Black flaking	4.4%	0.6	7.5%	4.7	3.6%	1.9	< 0.05
Black scaling	4.1%	2.8	1.7%	1.2	1.1%	0.9	< 0.01
Black soiling	38.6%	3.9	16.0%	2.7	6.4%	2.7	< 0.01
Total blackened stone	47.0%	4.9	25.1%	4.5	11.1%	4.7	< 0.01

Table 5.2 Descriptive statistics and ANOVA for each cluster formed by K-means clustering. (p values of < 0.01 give strong evidence of a significant difference between means of the three clusters whereas p values of < 0.05 only give some evidence of a significant difference.)

Weathering forms	Cluster 1 Cluster 2	Cluster 1 Cluster 3	Cluster 2 Cluster 3
Black flaking	---------	--------	< 0.05
Black scaling	< 0.05	< 0.01	--------
Black soiling	< 0.01	< 0.01	< 0.01
Total blackened stone	< 0.01	< 0.01	< 0.01

Table 5.3 Results of post-hoc comparison of means. Tukey Honest significant difference test for unequal sample sizes was used. (p values of < 0.01 give strong evidence of a significant difference between the means of two clusters whereas p values of < 0.05 only give some evidence of a significant difference.)

cluster 1, with the highest percentage of total blackened stone, are situated in central areas of the conurbation with one exception just north of the conurbation. Members of cluster 2, with an intermediate amount of total blackened stone, are generally inside the conurbation, but also extend to the north and are skewed slightly towards the east. Members of cluster 3, with little total blackened stone, are generally outside the conurbation or on the fringes to the east, south and west (Figure 5.2). This pattern suggests that urbanisation may increase the amount of total blackened stone, but to examine this further isometric lines, representing the percentage of total blackened stone for each building, were plotted onto the base map (Figure 5.3). There is a noticeable gradient, with values increasing from less than 10% in rural areas to the west to greater than 40% in the centre of the conurbation and decreasing to less than 20% in rural areas to the east. Changes from south to north are less clear, but it can be seen that in rural areas to the south values are typically below 20%, increasing in the centre to more than 40%, which is maintained to the north of the conurbation.

DISCUSSION

The isometric lines of total blackened stone and the cluster analysis results suggest that buildings in urban areas of the West Midlands experience up to four times more total blackened stone than buildings in rural areas. This general pattern is complicated by local factors exerting an influence within the conurbation. The isometric lines show that the highest cover of total

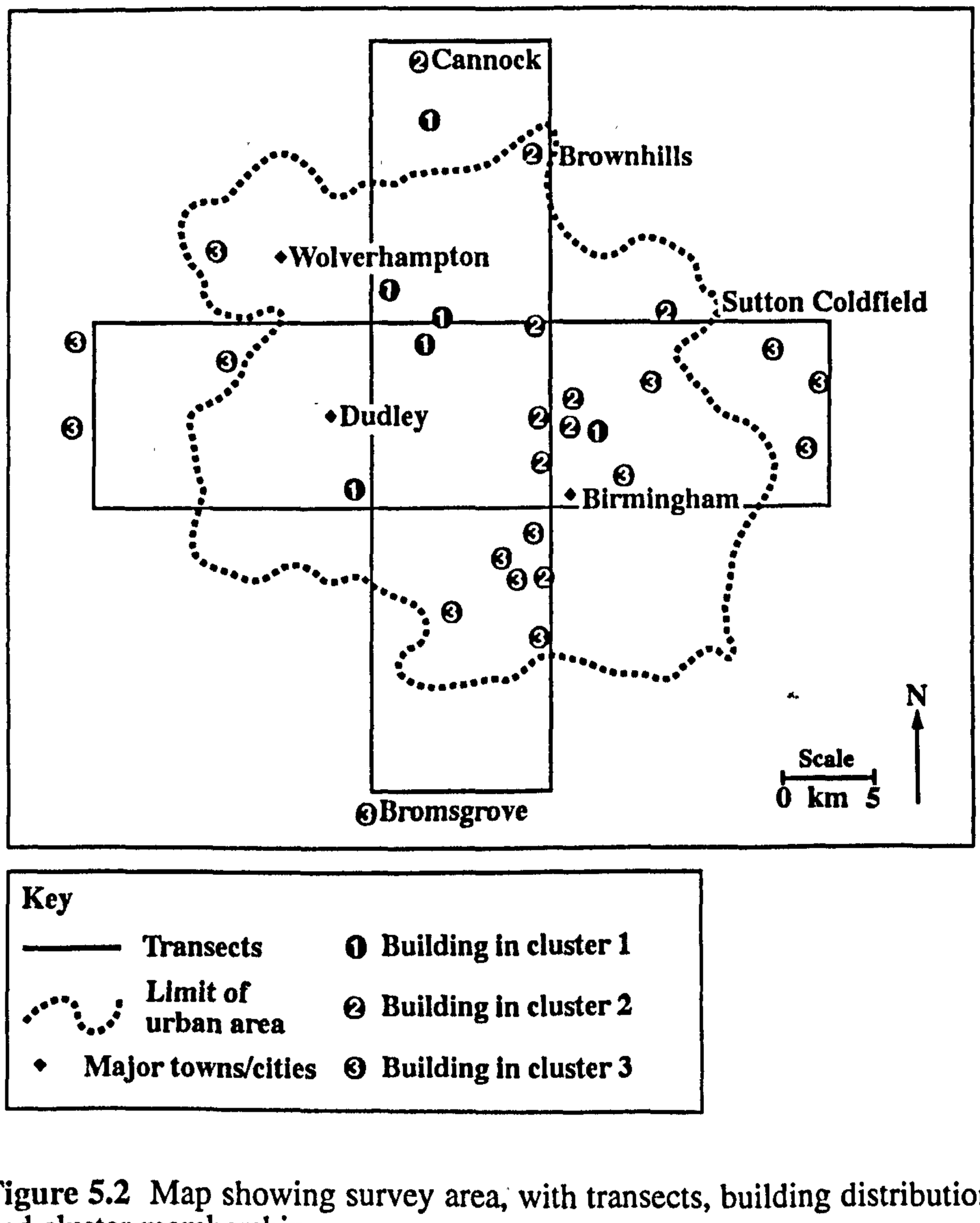

Figure 5.2 Map showing survey area, with transects, building distribution and cluster membership.

blackened stone occurs in an area crossing the middle of the conurbation from approximately north to south. A limb of relatively high cover also extends from the centre of the conurbation east above Birmingham (Figure 5.3). Various factors, such as relief or degree of exposure, could cause this distribution, but the most convincing factor is the location of industry. Major industrial emitters were identified in the 1960s by the national survey of air pollution. The location of these emitters compares closely to the isometric lines of total blackened stone (Figure 5.4). The central region has the

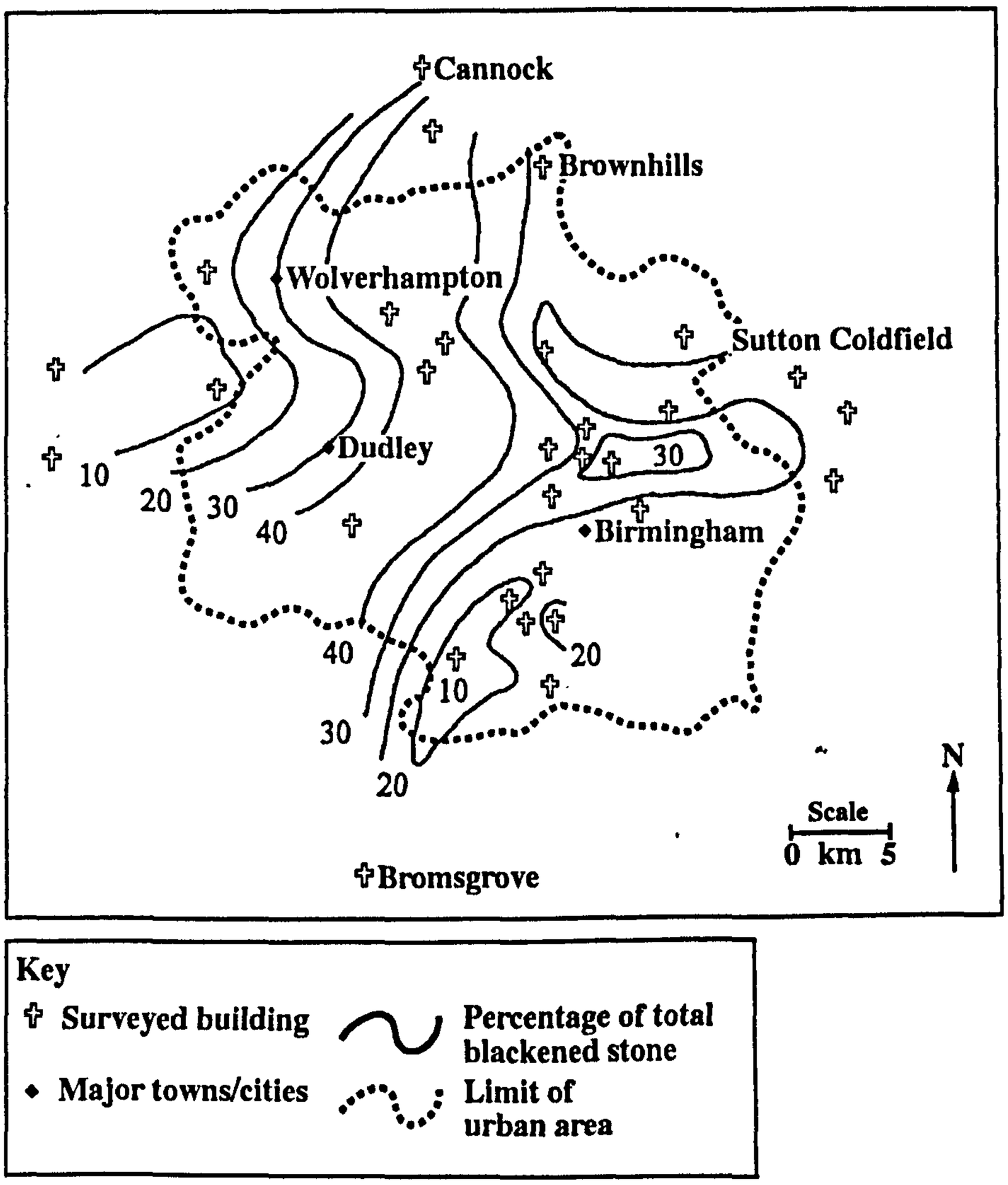

Figure 5.3 Map of survey area showing isometric lines representing percentage of total blackened stone.

densest concentration of emitters and the limb of relatively high total blackened stone north of Birmingham has a relatively high concentration. To fully explain the role of industry, however, it is necessary to consider the location of industry for the last 150 years (coinciding with the age of these buildings), and the type and amount of atmospheric pollutants they released. Data on the latter are especially limited, and industrial locations and activities have changed over time. A survey of the conurbation in the 1940s mapped the location of industry, indicating its historical distribution (Figure 5.5). It is noteworthy that the heavier industries, such as iron production,

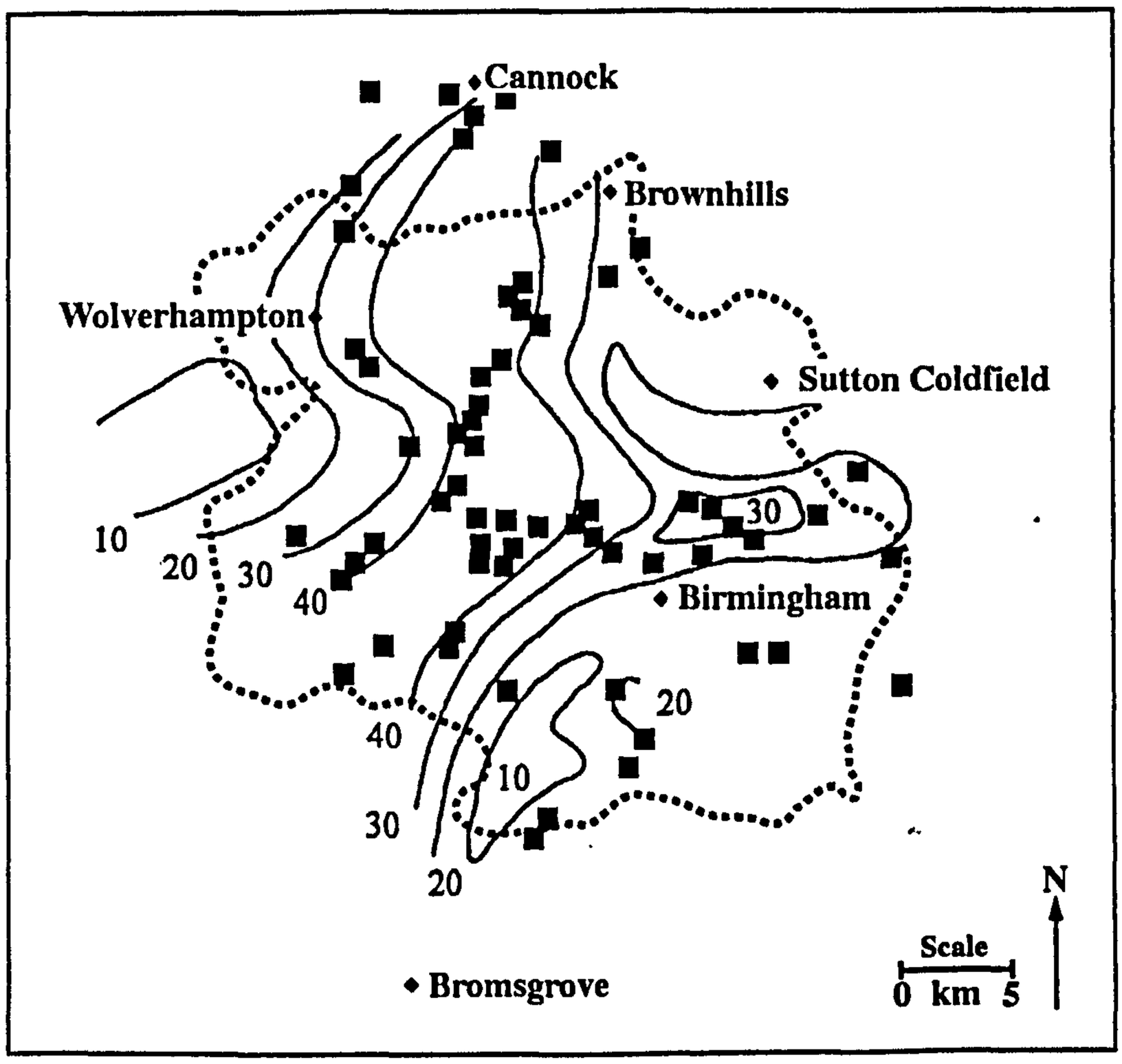

Figure 5.4 Map of survey area showing the distribution of major industrial emitters identified by the national survey of air pollution 1961–1971 (Warren Spring Laboratory, 1973). Isometric lines represent percentage of total blackened stone.

occupied a central location, especially between Birmingham and Wolverhampton, which may account for the highest percentage of total blackened stone occurring in this area.

The increase in total blackened stone, due to urbanisation and industrialisation, alters the appearance of the buildings, but the possible damaging influences of soiling warrants further consideration. Previous research

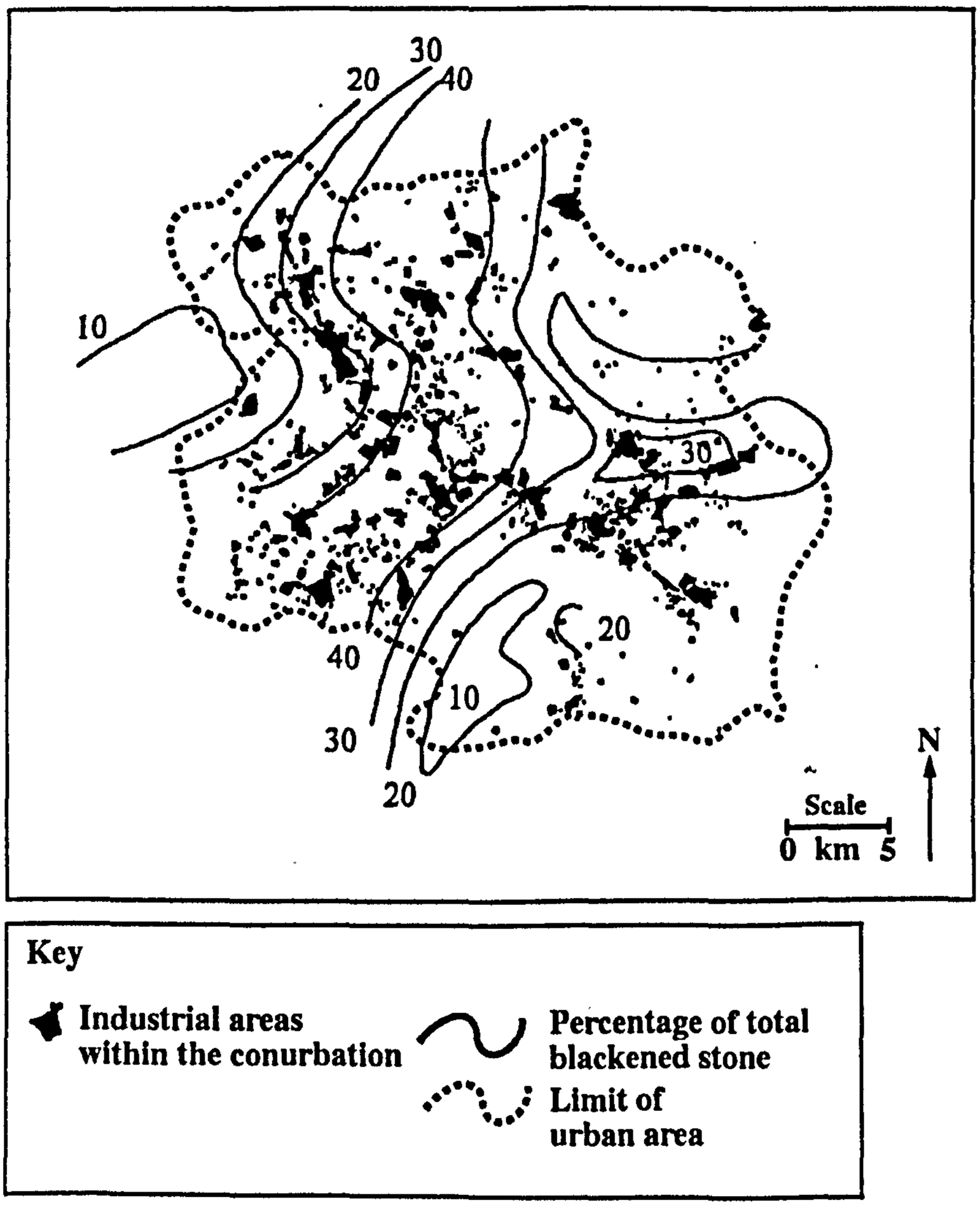

Figure 5.5 Map of survey area showing the distribution of industrial areas within the conurbation in the 1940s (West Midlands Group, 1948). Isometric lines represent percentage of total blackened stone.

reports black crusts to have a varied composition, but generally consist of inorganic particles such as flyash, organic materials such as algae and precipitates such as gypsum. A microcatchment experiment carried out on ferruginous quartz arenites, similar to those used in these buildings, has found that on average 66 mg m^{-2} $week^{-1}$ of solid particulate matter was deposited and held by sandstones exposed in Wolverhampton. These particulates were rich in silicon, aluminium and iron, with considerable deposits of calcium. On these sandstones, with little calcareous material, deposition of particulate

matter may be an important source of calcium necessary for gypsum formation. Further to this, the deposition of iron may catalyse gypsum formation. Scanning Electron Microscopy (SEM) examination of a black scale collected from Wednesbury (NGR SO 987934), near the centre of the conurbation, showed the presence of a range of particulate matter, predominantly coal fly ash, identified by its glassy and spherical form. This is not surprising, since historically the local source of fuel has been the indigenous Carboniferous Coal Measures.

In addition to chemical influences, black soiling may increase stone deterioration by physical weathering mechanisms. Black soiling lowers the albedo of stone, increasing absorption of incident solar radiation. Using a scale from zero to one, where zero is the minimum absorption of incident solar radiation and one the maximum, a red sandstone was found to have an absorptivity of 0.7, while coal flyash has a value of 0.95. This increase in the stones absorption of incident solar radiation may increase the importance of heating/cooling cycles, differential thermal expansion and wetting/drying cycles. These cycles produce stresses in the stone, but also increase dissolution/crystallisation cycles and hydration/dehydration cycles of gypsum, hence exacerbating stress. Previous research has commented on the possible damaging effects of black soiling trapping moisture behind the soiled outer layer of the stone. If black soiling totally covers sandstone, water absorption can be reduced from 0.68 l m^{-2} $hour^{-1}$ for unsoiled sandstone to 0.07 l m^{-2} $hour^{-1}$. Any drying occurs at the most permeable area, enhancing gypsum concentrations in this area and hence localised stone breakdown. This may be one reason why enhanced deterioration is often seen at the edges of ashlar, as the stone/mortar interface may provide a gap in the layer of black soiling. Additionally, during low temperatures, freezing may occur, forcing water to expand in a confined space behind the black soiling. This generates further stresses which may enhance deterioration and indeed rapid stone breakdown has been reported following a severe frost.

Considering these potentially deleterious effects of black soiling enables a generalised three stage model of the breakdown of black soiled sandstone to be proposed (Figure 5.6). This model provides a convenient summary of the mechanisms operating, however, the actual importance of each process, and whether they occur at all, will depend upon the properties of the stone and the environment it is exposed to. Presumably, these variables will also be decisive in whether black flaking or black scaling is formed. To examine whether these forms of detachment are proportional to the amount of total blackened stone, the share (%) of total blackened stone attributed to each weathering form was calculated for the three clusters of building (Table 5.4). Black scaling is reasonably consistent for all clusters and typically accounts for about 9% of the total blackened stone. Black flaking is less consistent, accounting for approximately 30% of the total blackened stone for clusters 2 and 3, but only 9% for cluster 1. The reasons for this are unclear, but it must be considered that the surveying technique only recorded the weathering forms present at the time of surveying. Therefore, if black flakes had already detached from many of the more

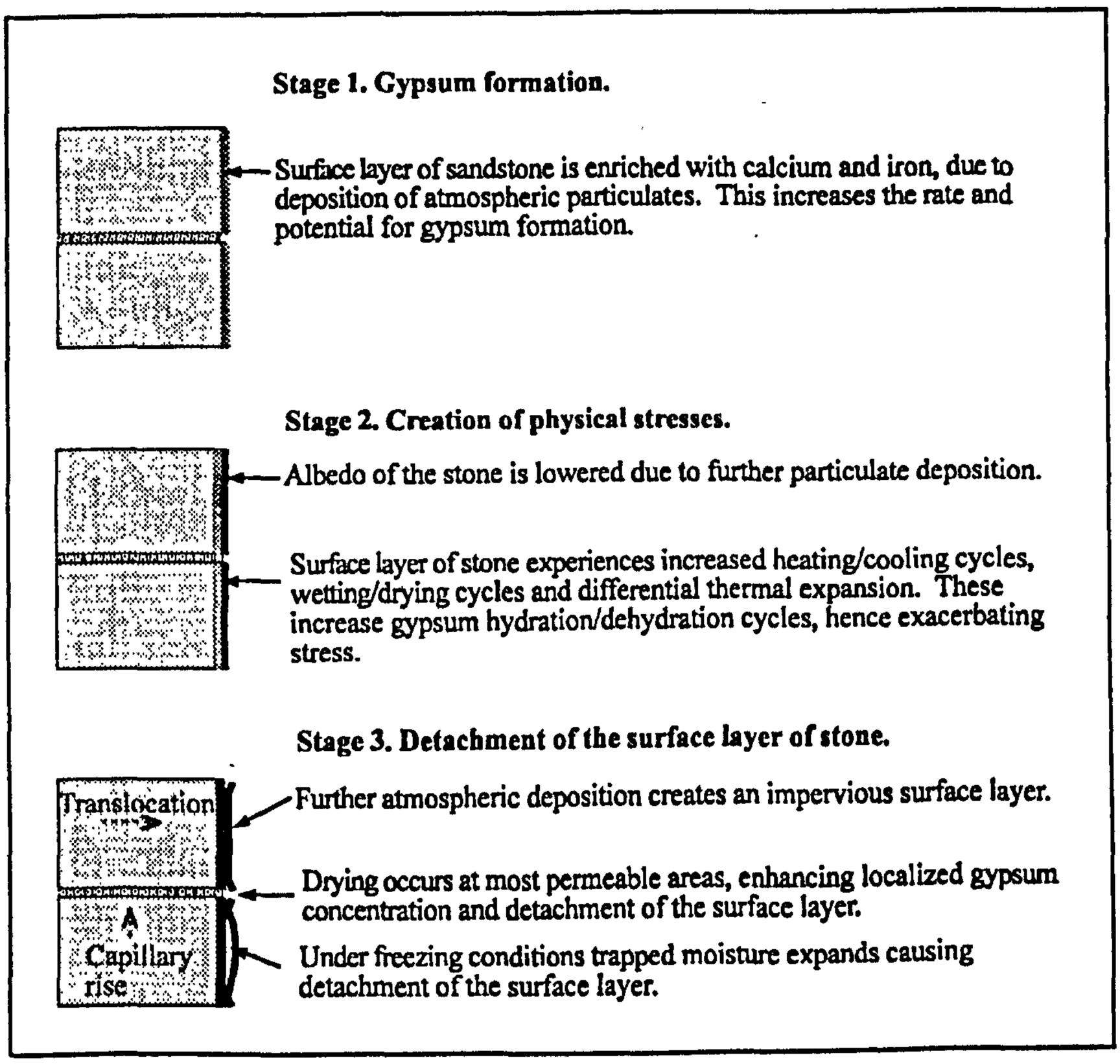

Figure 5.6 Generalised three stage model of the breakdown of heavily soiled sandstone.

severely soiled buildings in cluster 1, this form of weathering would be underestimated. Although it is often apparent that flaking or scaling has occurred, recording the actual type of flaking or scaling is not possible. It may be this limitation causing the poorer statistical significance for black flaking and black scaling shown by the post-hoc comparison of means (Table 5.3).

Weathering forms	Cluster 1	Cluster 2	Cluster 3
Black flaking	9.3%	29.8%	32.4%
Black scaling	8.7%	6.7%	9.9%
Black soiling	82.0%	63.5%	57.7%

Table 5.4 Percentage share of total blackened stone attributed to each weathering form.

CONCLUSIONS

Recording the percentage of stone covered by various weathering forms has enabled a quantification of the amount of total blackened stone, with values from less than 10% in rural environments to values greater than 40% in urban areas. These data are supported by observations in Italy where black soiling of sandstone was noted to be more severe in urban than in rural areas. There is also evidence that sandstones in more industrial areas experience the highest amounts of total blackened stone. In the West Midlands the use of coal as the dominant domestic and industrial fuel appears to have been an important source for much of this soiling, and this has a potentially deleterious effect upon the stone.

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References

Bluck, B. and Porter, J. (1991) Sandstone buildings and cleaning problems. *Stone Industries* **26**: 21–27.

Cheng, R., Mohnen, V., Shen, T., Current, M. and Hudson, J. (1976)

Characterisation of particles from power plants. *Journal of the Air Pollution Association* **26**: 787–790.

Elfving, P., Panas, I. and Lindqvist, O. (1994) Model study of the first steps in the deterioration of calcareous stone: III. Manganese and iron mediated sulphation of natural stone. *Applied Surface Science* **78**: 373–384.

Fitzner, B., Heinrichs, K. and Kownatski, R. (1992) Classification and mapping of weathering forms. In J. Rodrigues, *et al.* (eds) *7th International Congress on Deterioration and Conservation of Stone,* Lisbon, Portugal, 15–18 June, pp. 957–968.

Halsey, D., Dews, S., Mitchell, D. and Harris, F. (1995) Real-time measurements of sandstone deterioration: A microcatchment study. *Building and Environment* **30**: 411–417.

Halsey, D., Mitchell, D., Dews, S. and Harris, F. (1995) The effects of atmospheric pollutants upon sandstone: Evidence from real-time measurements and analysis of decay features on historic buildings. In J. Kamari, *et al.* (eds) *Proceedings of the 10th World Clean Air Congress, Volume 3,* Espoo, Finland, 28 May–2 June, FAPPS, Helsinki.

Howard, P. (1991) *An Introduction to Environmental Pattern Analysis.* The Parthenon Publishing Group, New Jersey.

McGreevy, J.P. (1985) Thermal properties as controls on rock surface temperature maxima, and possible implications for rock weathering. *Earth Surface Processes and Landforms* **10**: 125–136.

Sabbioni, C. and Zappia, G. (1992) Decay of sandstone in urban areas correlated with atmospheric aerosol. *Water, Air and Soil Pollution* **63**: 305–316.

Siegel, R. and Howell, J. (1972) *Thermal Radiation and Heat Transfer.* McGraw-Hill, New York.

Smith, B.J., Magee, R.W. and Whalley, W.B. (1994) Breakdown patterns of quartz sandstone in a polluted urban environment: Belfast, N. Ireland. In D. Robinson, and R.B.G. Williams (eds) *Rock Weathering and Landform Evolution.* J. Wiley & Sons, Chichester, pp. 131–150.

Threlkeld, J. (1970) *Thermal Environmental Engineering* (2nd edn). Prentice Hall, New Jersey.

Warren Spring Laboratory (1973) *National survey of air pollution 1961–71.* HMSO, London.

West Midlands Group (1948) *Conurbation: a planning survey of Birmingham and the Black Country.* The Architectural Press, London.

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